(NEU-)ANTRAG AUF EIN STIPENDIUM IM RAHMEN DES EMMY NOETHER-PROGRAMMS, PHASE II

0.1 PROJECT TITLE

AMIGA: **A**DAPTIVE **M**ULTI**G**RID **I**NVESTIGATIONS OF **G**ALAXY **A**SSEMBLY

0.2 ABSTRACT

The observational and theoretical study of galaxy formation and evolution is one of the fields in astrophysics that will see tremendous progress in the next decade. A coherent picture of the physics involved drives the development of the next generation of instrumentation and demands adeptness with the latest sophisticated computational modeling techniques. The project outlined in this application describes a powerful adaptive multigrid code which includes self-gravity, hydrodynamics and star formation and will be employed for high-resolution cosmological simulations of galaxy formation and evolution. This non-proprietary code will be a unique contribution to the entire astronomical community's effort to understand the complicated physics of galaxy formation.

0.3 RESEARCH FIELD

Astronomy & Astrophysics:
computational cosmology – N-body simulations – galaxy formation and evolution – dark matter

1 **AMIGA**: **A**daptive **M**ulti-Grid **I**nvestigations of **G**alaxy **A**ssembly

SUMMARY

There is mounting, if not overwhelming, evidence that the Cold Dark Matter (CDM) model provides the most accurate description of our Universe. Observations point towards a Universe comprised of 28% dark matter, 68% dark energy, and luminous baryonic matter (i.e. galaxies, stars, gas, and dust) at a mere 4% (cf. Spergel et al. 2003). This so-called "concordance model" induces hierarchical structure formation whereby small objects form first and subsequently merge to form progressively larger objects (e.g. White & Rees 1978; Davis et al. 1985).

When used to model the dynamics of a collisionless system, as it is the case for dark matter, an N-body code solves the collisionless Boltzmann equation by the method of characteristics (e.g. Leeuwin, Combes & Binney 1993). The characteristics, on which the phase-space density f is constant, are the possible trajectories of particles in the system's gravitational potential, Φ. The simplest approach to managing this task is to sample phase-space using N particles, i.e. the mere purpose of such codes is to calculate the gravitational interactions of N particles and hence the name N-body code. And over the last 30 years great progress has been made in the development of N-body codes that actually model the distribution of dark matter (with or without the presence dark energy) throughout the Universe, resulting from seed inhomogeneities produced shortly after the Big Bang. Algorithms have advanced considerably since the first N^2 particle-particle codes (Aarseth 1963; Peebles 1970; Groth et al. 1977); we have seen the development of tree-based gravity solvers (Barnes & Hut 1986), mesh-based solvers (Klypin & Shandarin 1983), combinations of direct summation techniques and grid based Poisson solvers (Efstathiou et al. 1985) and multiple strands of adaptive and deforming grid codes (Villumsen 1989; Suisalu & Saar 1995; Kravtsov, Klypin & Khokhlov 1997; Bryan & Norman 1998; Knebe, Green & Binney 2001). The result of such research has been highly reliable, cost effective codes (cf. Bertschinger 1998).

However, astrophysics is based on observing photons emitted due to atomic processes and only when the governing physics is included in the theoretical modeling we will have a fair chance of understanding how the Universe formed and evolved; not only do we need to model dissipationless dark matter (and dark energy), but baryonic processes have to be included in any cosmological simulation if there is to be a reasonable hope that it will capture the essence of galaxy formation. My strong belief is that the future of "Computational Cosmology" lies with codes that are capable of performing the highest resolution simulations of self-consistent galaxy formation and I think adaptive multi-grids[1] is the appropriate technique to target this issue.

The main objectives of this application are to develop and make widely available a robust, adequately documented adaptive multi-grid code for high-resolution simulations of the self-consistent formation and evolution of galaxies, including all governing equations for collisionless dark matter, dark energy and, most importantly, this code will also include all the relevant baryonic processes that profoundly influence such objects. Simultaneously the code will be used to address some of the astrophysical problems currently under debate.

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[1] Adaptive Multi-Grid is also known as Adaptive Mesh Refinement (AMR).

1.1 AIMS AND BACKGROUND

1.1.1 COSMOLOGY - WHERE DO WE STAND, WHERE DO WE GO ?

Cosmology - the study of the formation and ultimate fate of structures and galaxies throughout the Universe - is without a doubt the dominant field of astrophysics today. And in the last few years theoretical and observational studies have begun to converge as we enter the era of "Precision Cosmology". A picture has emerged in which contemporary structures have evolved by gravitational amplification of seed inhomogeneities that are likely of quantum origin. This picture ties together measurements of the cosmic background radiation, estimates of the primordial abundances of the light elements, measurements of the clustering of galaxies and, to a more limited extent, the characteristic properties of individual galaxies. The interpretation of the high-quality observational data becoming available (SDSS[2], 2dF[3], BOOMERanG[4], WMAP[5], etc.) depends heavily on (extremely) high-resolution numerical simulations of structure formation and evolution, a practice which might be referred to as "Precision Modeling".

Our current understanding of the Universe rests on some important assumptions and one of them is that luminous matter (i.e. baryons) contributes only a small fraction of the mean density in the Universe, the bulk being made up of some combination of vacuum energy and dark matter (cf. Spergel et al. 2003). However, dark matter plays a central role in structure formation because it (i) dominates the matter content of the Universe and (ii) only interacts gravitationally. It is already free to cluster in the radiation dominated era when the baryons are effectively locked to the relatively incompressible radiation fluid. Consequently, at the era of decoupling, when the observable baryons are at last able to cluster, they quickly fall into ready-made structures in the dark-matter density field. The governing equations that one needs to solve in order to follow the evolution of dark matter are the coupled collisionless Boltzmann and Poisson equations. The standard technique for solving this system is N-body simulation and models based on the so-called "concordance cosmology" (i.e. ΛCDM) yield consistent interpretation of observations – at least on super-galactic scales. But a self-consistent picture of galaxy formation should rest not only on the modeling of dark matter but include the most accurate treatment of all the complicated physical processes that give rise to what actually is being observed: stars and gas in galaxies.

1.1.2 WHAT IS THE PROBLEM ?

The luminous parts of galaxies are baryon-dominated, and their structure must reflect the complexities of gas- and magneto-hydrodynamics, as well as radiative transfer; galaxies are forming as a result of gravitational amplification of primordial density fluctuations *together* with the action of such complicated physical processes. Even though models and observations seem to have converged on large scales, they do not tie together on sub-galactic scales. Dark matter N-body simulations predict at least an order of magnitude more satellite galaxies orbiting within a galactic halo than observed (Klypin et al. 1999, Moore et al. 1999a). Moreover, high resolution observations of galaxy rotation curves are incompatible with the steep dark matter cusps found in such simulations (cf. de Blok, Bosma & McGaugh 2003). Attempts to solve these

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[2] `http://www.sdss.org`

[3] `http://www.mso.anu.edu.au/2dFGRS`

[4] `http://cmb.phys.cwru.edu/boomerang/`

[5] `http://map.gsfc.nasa.gov/`

problems are simply first steps and most of them do *not* include a self-consistent treatment of all the physics involved. More refined and sophisticated techniques need to be developed to understand and interpret observations of high- and low-redshift galaxies and confirm our current belief in the hierarchical structure formation scenario. Then (and only then) there is hope to obtain the outstanding answers to the problems alluded to above and other puzzling issues of galaxy formation as for instance: how do galaxies obtain their gas?; is the morphology of galaxies regulated by the mode of gas accretion?; why is there a mismatch between the local baryon density and the one observed at high redshift?

Some groups have side-stepped the problem of simulating galaxy formation by developing a semi-analytic approach (e.g. Kauffmann, White & Guiderdoni 1993; Baugh et al. 1999). This approach has hitherto provided almost the only connection to observation, but it is open to the objection that it is little more than a multi-parameter fit to rather sparse data. Any conclusions drawn from semi-analytical models are less secure than ab-initio calculations invoking physics in a self-consistent manner. Consequently, intensive efforts continue world-wide to make progress with simulations that do include not only dark matter but also baryonic physics.

1.1.3 WHAT IS THE PLAN ?

During the last two decades, significant progress has been made in developing numerical methods, and numerical simulations of cosmic structure formation have become a powerful tool to accompany, interpret, and sometimes lead cosmological observations. There are currently two types of codes available, tree codes and adaptive particle-particle-particle-mesh (AP^{3}M) codes, which both are dependent on direct particle-particle (PP) summations. I think this approach can be improved on and have therefore developed a new N-body code `MLAPM` (**M**ulti-**L**evel-**A**daptive-**P**article-**M**esh) based on adaptive grids. It is now important if not mandatory to implement baryonic processes that are relevant for the formation and evolution of galaxies (e.g. gas dynamics, star formation, supernova feedback, and metal enrichment). Moreover, also parallelisation needs to be targeted since we are entering an era in which massively parallel computers lie within the budgets of single research groups. Using this new code, which is going to be freely available, we will be able to address and contribute to solutions of our yet incomplete understanding of galaxy formation.

1.2 SIGNIFICANCE AND INNOVATION

1.2.1 WHAT ARE THE COMMONLY USED N-BODY METHODS ?

Since the pioneering simulations in the 70's, a great deal of effort has gone into producing powerful N-body codes for cosmological simulations. Various techniques have been developed to allow for more complex and detailed studies of the formation of structures in the Universe. I am going to introduce the basic ideas behind them and compare them to the adaptive (multi-)grid approach to elaborate on the significance and innovation of the method.

The first simulations evaluated the forces on particles by direct summation of the Newtonian interaction between particle pairs (Peebles 1970; Haggerty & Janin 1974). Tree codes (Barnes & Hut 1986; Springel, Yoshida & White 2000; Dehnen 2000) radically reduce the cost by grouping distant particles into aggregates, and then summing over such aggregates rather than over individual particles. Particle-Mesh (PM) codes (Hohl 1978; Hockney & Eastwood 1988) estimate the density on a grid and then use discrete Fourier transforms (DFTs) to convolve the

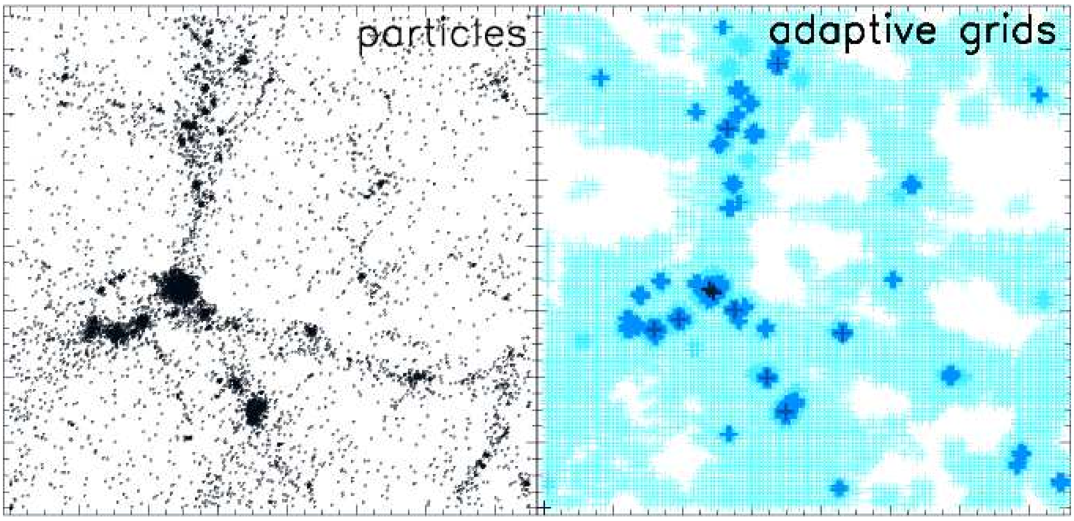

Figure 1: A "live" cosmological simulation (left panel) and the adaptive grids invoked by MLAPM to increase spatial resolution in high-density regions (right panel).

density with the Green's function of Poisson's equation. This technique is extremely fast but suffers from the limitation that the use of DFTs mandates the use of a regular grid, and such a grid cannot adequately represent a highly clustered distribution of particles developing as part of the filamentary and sheet-like structures of the Universe. In a particle-particle-particle-mesh (P^3M) code, a PM calculation that uses a coarse grid yields the long-range component of the forces, while direct summation of additional forces from near neighbours completes the calculation (Hockney & Eastwood 1988; Efstathiou et al. 1985). As clustering develops, large numbers of particles accumulate in a few cells of a P^3M code's coarse grid, and the direct summation part of the calculation becomes prohibitively costly again. In an adaptive P^3M (AP^3M) code this situation is remedied by replacing the direct summation in a region of high density by an additional P^3M calculation, in which a fine grid covers only the dense region (Couchman 1991; Couchman et al. 1995). This process is recursive but we like to stress that these adaptive grids are merely introduced for timing reasons and hence have no effect on the resolution of the simulation. In all mentioned techniques small scale structures depend on the reliability of the direct PP summation.

One might pose the question if it is actually legitimate to resolve structures below the (initial) inter-particle separation as there were no such fluctuations present in the initial conditions. The answer to this is question is yes for two reasons. First, the evolution of power on small scales is driven by the transfer of power from large scales and hence it is important to follow it appropriately (Hamana, Yoshida & Suto 2001). Second, the systems under investigation are highly chaotic and by the time a galaxy nucleus forms dissipationally, all memory of the initial conditions on these small scales has been lost.

1.2.2 WHAT IS ADAPTIVE (MULTI-)GRID ?

With a sufficiently adaptive grid the entire force can be calculated on the grid alone: in order to bypass the lack of resolution on small scales MLAPM does not introduce a PP summation (like in AP^{3}M codes), but it rather uses arbitrarily shaped finer grids[6] in regions where the density exceeds a given value and solve Poisson's equation using Brandt's multi-grid method (Brandt 1977)[7]. This whole process is implemented fully recursively, enabling one to follow the evolution of cosmic structures like sheets and filaments in the most natural way (cf. Fig.1). With this method `MLAPM` is only spending CPU time as well as computer memory on regions of interests. Several considerations suggest that this approach has greater potential than the more widely used tree and AP^{3}M technologies. Immediately apparent advantages of adaptive grids are that they *naturally* admit (i) periodic boundary conditions, (ii) adaptive softening, and (iii) individual time-steps. Part (i) is mandatory for all cosmological codes and even though most tree and AP^{3}M codes feature individual time-steps, they all lack adaptive softening. `MLAPM`'s force resolution adjusts to the underlying physical problem whereas in tree and AP^{3}M codes the resolution stays fixed (either in comoving or in physical coordinates) during the course of the simulation. This latter limitation may lead to unwanted numerical effects such as particle scattering in low density regions (Knebe et al. 2000) and increased two-body relaxation (Binney & Knebe 2002). But most importantly, `MLAPM` provides a framework in which to do grid-based hydrodynamics.

1.2.3 WHY ARE BARYONS SO IMPORTANT ?

The current picture of galaxy formation rests upon dark matter potential wells developing hierarchically and acquiring angular momentum via tidal torques with neighbouring protohalos. Baryons, capable of releasing energy through atomic processes, cool and dissipate their energy while conserving angular momentum to form a self-gravitating (gaseous) disk. This disk becomes unstable to fragmentation and starts forming stars. At the end of the stars' lifetime supernova explosions not only release energy into the surroundings (which has a profound influence on the evolution of the galaxy), but also enrich the intergalactic (and intra-cluster) medium with "metals"[8]. Galaxy morphology (e.g. the appearance as spiral, elliptical, irregular, and barred galaxies) itself might be understood as a transient phenomenon where in simplified terms major mergers of spiral galaxies lead to the formation of (giant) elliptical galaxies which in turn grow disks via a steady accretion stream of gas (cf. Hernquist 1992; Naab & Burkert 2001; Steinmetz & Navarro 2003). If dark matter exists and is collisionless, we have a fair idea of how it will cluster. Our poor understanding of galaxy formation arises in part because baryons, being dissipative, cluster much more strongly than dark matter, and galaxies form from the most strongly clustered component. Only simulations including *all* the relevant physics (and not only gravity) can give rise to an understanding of galaxy formation and evolution.

1.2.4 WHY GRID-BASED HYDRODYNAMICS RATHER THAN ANYTHING ELSE ?

One has to think of which technology is likely to make the biggest impact in the future. Two considerations bear on the answer to this question. One is ease of parallelisation and the other the ease of including gas dynamics. The governing equations of baryons are those of hydrodynamics, and these are most efficiently solved on a grid[9] (Kang et al. 1994; Müller

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[6] Individual cells are refined (de-refined) if the density in that cell exceeds (falls below) a preselected value.

[7] Since `MLAPM`'s refinement grids are of arbitrary shape no DFT method can be applied

[8] Elements heavier than helium are referred to as "metals".

[9] Computational fluid dynamics is not only limited to astrophysical problems. It also has a great application for everything that deals with hydrodynamical equations as for instance meteorology, oceanography and aero-

1997; Norman & Bryan 1998; Falle 2000; Teyssier 2002; Norman 2004). Another way of dealing with baryonic physics is to trace thermodynamical variables using representative mass elements. This is the (grid-less) smooth-particle-hydrodynamics (SPH) technique (Lucy 1977; Gingold & Monaghan 1977; Monaghan 1992). SPH has been the favourite method of choice for cosmological tree and AP^{3}M codes due to its "particle nature" and hence ease of implementation (e.g. Hernquist & Katz 1989; Navarro & White 1993; Couchman et al. 1995; Springel, Yoshida & White 2001).

One can immediately name the (dis-)advantages of both these methods: grid-based algorithms are well suited for resolving shocks but the spatial resolution is dictated by the grid spacing. SPH methods have (in principle) unlimited spatial resolution but artificial viscosity needs to be added in order to properly capture shocks. Moreover, the particles upon which SPH is based introduce a fixed mass scale[10], with the consequence that it is unreliable both in low-density regions, where the particle density is low and the numerical viscosity correspondingly high, and in high-density regions, where only a small, but extremely interesting, mass fraction may reside. For instance, the entire evolution of an L^* galaxy and its hinterland (which will extend to $\sim$ 1Mpc from the galactic nucleus) may be profoundly influenced by energy released by a few $\times 10^7 M_\odot$ of gas that forms a nuclear star-burst and/or feeds an active galactic nucleus. The agency by which energy released in the inner 50pc of the galaxy influences intergalactic gas at a distance of $\sim$ 1Mpc may be a fast wind that carries that energy at extremely low density. It will be essential to follow the detailed structure of the inner starburst as well as that wind requiring a spatial resolution of $\lesssim$ 50pc. Additionally, masses of the order $\sim 10^7 M_\odot$ must be resolved, which implies SPH particles with masses $\lesssim 3 \times 10^4 M_\odot$ (Navarro & White 1993). The total baryonic mass of the galaxy and its enveloping IGM will be $\sim 10^{12} M_\odot$ and hence $\sim 3 \times 10^7$ SPH particles are required per simulated galaxy. Both dark-matter simulations and observations have now established that galaxies are profoundly influenced by their surroundings, so that dozens of galaxies have to be formed in a single simulation. We arrive at the conclusion that in excess of 10^9 SPH particles will be required. On the other hand, at any given time, only an extremely small fraction of the baryons will be in regions requiring resolution at the $10^4 M_\odot$ level. Only an adaptive multi-grid calculation, which has no pre-determined mass resolution and adjusts its spatial resolution to the problem, can resolve the galaxy centre (and said wind) at high resolution, and the rest of the galaxy at the more appropriate lower resolution. However, this inherent superiority of grid-based hydrodynamics is realized *only* when one uses *dynamical grids* that adapt to the evolving matter distribution. Therefore, software such as `MLAPM` that provides such grids is of considerable strategic importance and should be used both for solving Poisson's and the hydrodynamics equations.

1.2.5 WHY A NEW CODE ?

Workers in hydrodynamics have produced codes with adaptive grids, and in some cases the grids, like `MLAPM`'s, have arbitrary geometry. However, to our knowledge, all these arbitrary-geometry hydrodynamical grid codes are proprietary products and hence I was unable to adapt such a pre-existing code. Several groups have tried using the adaptive-grid technology for cosmological

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plane wing design (cf. Norman 2004). And most of the techniques development in those areas are also based on (adaptive) grids.

[10] Workers accustomed to N-body simulations may find fixed mass resolution normal, because it arises naturally in the solution of the collisionless Boltzmann equation. It is however *not* natural in hydrodynamics.

simulations (Gnedin 1995; Pen 1998; Norman & Bryan 1998) but my belief is that I can improve on previous work. Gnedin (1995) and Pen (1998) start with a Cartesian grid and let it distort so as to increase spatial resolution in some regions. This procedure though has the drawback of producing significantly non-cubical cells which can be avoided by adaptively refining the grids as done in `MLAPM`. Norman & Bryan (1998) enhance the resolution of a basic Cartesian grid by placing finer grids over dense regions. This approach is similar to `MLAPM` but different: these refinements[11] themselves have to be cubical and non-overlapping. Consequently, the grids are not capable of following a highly non-symmetric density distribution like, for instance, the filamentary structure of the Universe.

An elaborate study that compared the formation of a single galaxy cluster using SPH- as well as grid-based simulations showed that there are severe discrepancies between those two competing techniques: all grid-based codes produce a temperature profile for that galaxy cluster that is still rising in the central parts while the SPH simulations are showing a distinct core (Frenk et al. 1999). The solution to this puzzle is still pending. More recently, O'Shea et al. (2003) compared the adaptive mesh refinement code ENZO (Bryan & Norman 1998) to the publicly available tree-SPH code GADGET (Springel, Yoshida & White 2001). They analysed dark matter only simulations as well as runs with a non-radiative (adiabatic) gaseous component. Even though some of the results seem to indicate that aforementioned discrepancy between grid-based and particle-based solvers have diminished when using the "entropy conserving" implementation of GADGET, there still appears to be a great deal of uncertainty; in their study two different formulations for Eulerian hydrodynamics used with ENZO gave strikingly different results, especially in low-density regions. And there are indications that the piecewise-parabolic hydrodynamics solver gives more reliable results, even though the discrepancy in the results compared to GADGET is largest for this method; the hydrodynamics solver adopted from the ZEUS code[12] leads to too much entropy because of the artificial viscosity formulation (Mike Norman, private communication).

Only recently (March 1, 2004) the adaptive mesh-refinement code ENZO has been made publicly available[13]. In my opinion though it is important to develop the adaptive multi-grid approach independently, and in fact there are subtle differences to the approach for generating and dealing with the grid hierarchy, respectively. ENZO uses cubical, non-overlapping patches rather than individually refining and de-refining cells. Consequently, the grid cannot mimic accurately a nearly fractal density distribution of the type that gravitational clustering generates. In the end such an approach requires more computer and memory resources than actually needed to solve the problem with the appropriate resolution. `MLAPM`, on the other hand, only allocates resources for *exactly* that area of the computational volume that requires high resolution; the grids in `MLAPM` have arbitrary shape and are not restricted to be cubical or of any other (symmetric) geometry.

With the success of the project outlined in this application I would not only be able to add my share to an ongoing discussion about numerical techniques, but also provide another independent code for comparison as `MLAPM` will be freely available to the community.

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[11] A refinement is a spatially coherent collection of cells.

[12] `http://zeus.ncsa.uiuc.edu/lca_intro_zeus3d.html`

[13] `http://cosmos.ucsd.edu/enzo/`

1.2.6 SUMMARY

Astrophysics is the study of photons emitted by sources that are outside our area of reach. To understand their nature it is necessary to develop, subsequently verify and (hopefully) validate theoretical models of their formation and evolution. But only when these models incorporate the governing physics we will have a fair chance of understanding how the Universe formed and evolved; a great deal of baryonic processes (and not only gravity) has to be included in any cosmological simulation if there is to be a reasonable hope that it will capture the essence of galaxy formation. Robust and efficient numerical methods are required to handle this complexity. The future of "Computational Cosmology" lies with codes that are capable of performing the highest resolution simulations of self-consistent galaxy formation and it is not only my belief that adaptive multi-grids is the appropriate technique to target this issue (cf. Norman 2004).

1.3 APPROACH

`MLAPM` has been thoroughly tested and brought to the point at which it is faster than serial versions of the publicly available AP^{3}M code or the tree code GADGET when run in single-CPU mode (Knebe, Green & Binney 2001). The most urgent task now is to implement baryon physics as well as to tackle parallelisation. However, a balance has to be struck between the two aspects (i) astrophysics, and (ii) code development.

1.3.1 CODE DEVELOPMENT

BARYON PHYSICS With the current version of `MLAPM` I have already addressed controversial astrophysical problems regarding the cuspiness of dark matter halos and the abundance of substructure by investigating non-standard structure formation scenarios (Knebe et al. 2001; Knebe et al. 2002; Little, Knebe & Islam 2002; Knebe & Gibson 2003) and cross-checking for numerical artifacts (Knebe et al. 2000; Binney & Knebe 2001). The next step is to improve the simulations by implementing:

- hydrodynamics on the adaptive multi-grids:

  I intend to implement the third order accurate, shock capturing piecewise-parabolic-method (PPM) outlined in Bryan et al. (1995). However, the hydrodynamics part will be programmed "modular" so that it can be easily replaced with alternative techniques.

- cooling:

  In order to be able to form stars, the gas must undergo cooling. To model gas cooling I intend to use the cooling curves computed by MAPPINGS III[14] written by R.S. Sutherland. Those curves give cooling rates as a function of temperature as well as metallicity.

- star formation:

  The cooled gas needs to be transfered into stars, i.e. star particles will be created on-the-fly (cf. Cen & Ostriker 1992; Katz 1992; Tassis et al. 2002). Such a star particle is not an individual star but rather an association of many stars and will be distributed according to an appropriate initial mass function.

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[14] `http://www.mso.anu.edu.au/~ralph/map.html`

- feedback from supernovae explosions:

  A sophisticated chemical enrichment algorithm (neglecting instantaneous recycling, but including contributions from supernovae, stellar winds, and binaries), based upon that implemented with the `GCD+` package at Swinburne's Centre for Astrophysics & Supercomputing (Kawata & Gibson 2003), will be employed.

- software tools which allow the user to simulate observations:

  With the Virtual Observatory[15] on the horizon and the proposed inclusion of theoretical data "synthesized software telescopes" need to be developed that will allow the user to operate on simulation data in a similar manner to conventional telescopes.

Point 1-3 & 5 will be done in very close collaboration with the cosmology and galaxy group at the Astrophysikalisches Institut Potsdam and benefit from their experience in that research field. Further – as mentioned before – a recent study involving several tree-SPH and AMR codes lacked a coherent picture and showed severe differences in the results obtained with different techniques, respectively (Frenk et al. 1999). But even akin methods showed discrepancies which might be due to the fact that the simulations were run on different supercomputers and analysed using different analysis tools, respectively. Such a situation can clearly be avoided when the full analysis is done at *one* institution, i.e. the Astrophysikalisches Institut Potsdam, and overseen by one person. Moreover, being situated at the AIP will allow me to draw upon the expertise of its staff with their impeccable record on simulating galaxies using tree-SPH techniques.

The AIP also plays a major role in the German contribution to the international activities in creating a global Virtual Observatory (VO) network[16]. This involves an extension of the observational data base to simulation data. This project is labeled the "Theoretical VO" and it therefore appears natural to address the development of "software telescopes" operating on the theoretical data base at the AIP.

Point 4 will be done in very close collaboration with the cosmology group at Swinburne's Centre for Astrophysics & Supercomputing. The group has all the experience of dealing with these complicated physical processes which have been successfully implemented into their Tree-SPH code `GCD+` (Kawata 1999; Kawata 2001; Kawata & Gibson 2003).

PARALLELISATION Besides of the implementation of baryonic physics, parallelisation needs to be addressed, too. The Astrophysikalisches Institut Potsdam hosts one of the largest supercomputers dedicated to astrophysics alone in Germany which consists of 135 dual-CPU Linux PC's. It appears therefore mandatory to port `MLAPM` to this kind of Beowulf cluster using the freely available Message Passing Interference Standard[17] (MPI). The approach to this is to

- use an MPI-library FFT solver on the domain grid
- farm out spatially connected refinement patches to different CPU's

`MLAPM` steps through the various levels of refinement grids solving Poisson's equation on each level using isolated boundary conditions derived from the next upper level. It is therefore

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[15] `http://www.ivoa.net`

[16] `http://www.g-vo.org`

[17] `http://www-unix.mcs.anl.gov/mpi/`

possible to localize spatially connected refinement grids and send them to individual CPU's. The nature of cosmological simulations entails that in fact nearly every galaxy will be surrounded by such highly localized refinement grids and hence this approach to parallelisation can be understood as "simulating each galaxy in the computational volume on its own CPU". The latest release version of `MLAPM` already includes on-the-fly galaxy identification which in turn means that the tools to distribute the work onto a Beowulf-type supercomputer are already at hand.

Based upon a decade of experience in the field of computational cosmology, realistic estimates of the time to complete (i) Hydro-`MLAPM` and (ii) parallelisation is three years in total.

1.3.2 CODE TESTING

Substantial testing to assess the credibility of upgraded versions of the code is mandatory and should not be taken for granted in such an application. There are analytical solutions for simple test cases (ie. shock tube test (Sod 1978), the strong point explosion (Sedov 1959), etc.) allowing accurate gauging of the hydrodynamics solver. Moreover, under the assumption that the cooling function follows a certain functional form it is possible to derive a self-similar solution describing the collapse of a gas cloud (Abadi, Bower & Navarro 2000). Such a solution can be used to test the capability of the cooling implementation. There are also simple analytical reasonings that allow to identify the physical processes driving the evolution of the star formation history (Hernquist & Springel 2003). Such a recipe can be used to gauge the implementation of star formation in cosmological simulations. However, there is no straight forward method for testing the implementation of feedback though; energy released during a supernova explosion is simply deposited into a combination of kinetic and thermal energy into the surroundings.

1.3.3 ASTROPHYSICAL APPLICATIONS

The code development part of the project has to be complemented by scientific research based upon (improved versions of) `MLAPM`. I intend to target the following questions by means of (hydrodynamical) cosmological simulations:

- galactic archaeology or how did the Milky Way form?

  With the discovery of more and more stellar streams in our Milky Way halo as well as M31's halo (e.g., Navarro, Helmi & Freeman 2004), it is mandatory to understand the nature of this debris associated with currently dissolving satellite galaxies. The RAVE experiment[18] is designed to obtain phase-space information for more than 30mio. stars and hence even more streams are to be unveiled. I plan to provide theoretical models of the formation and evolution of such streams using ultra high-resolution simulations of the disruption of satellite galaxies within live dark matter host halos. This in turn will allows one to gain insight into the formation history of our very own Milky Way ("galactic archaeology").

- where do semi-analytical models for the Milky Way formation break down ?

  So far, models for tidally induced (stellar) streams have been based upon *fixed* potentials for the underlying dark matter host halo and analysing the orbits of artificially

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[18] `http://www.aip.de/RAVE`

created satellite galaxies within it (e.g. Peñarubbia et al. 2002; Hayashi et al. 2003; Johnston et al. 2002) and semi-analytical approaches (e.g. Taylor & Babul 2003; Taffoni et al. 20031), respectively. Such methods were, for instance, used to infer the shape of our own Milky Way trying to match the observational data of the stellar stream associated with the (currently disrupting) Sagittarius dwarf galaxy (cf. Ibata et al. 2001; Helmi 2003). Unfortunately there are limits to the predictive power of these (semi-)analytical methods and it would be more authentic to actually use halos that form *fully self-consistently* within the cosmological framework. Comparing such "live" streams to the more common approach of tracking artificially created satellites in static potentials will allow to validate the credibility of the latter technique.

- how is the galactic disk aligned with the shape of the dark matter halo?

  The orientation of the disk component of galaxies with respect to the shape of the surrounding dark matter halo still remains uncertain. In a recent study we reported an anisotropy in the spatial distribution of satellite galaxies indicating that they are preferentially found along the *major axis of triaxial dark matter halos* (Knebe et al. 2004). To now extent these findings and provide a possible explanation for the observed alignment of satellites with the *minor axis of the galactic disk* ("Holmberg effect", Holmberg 1969) simulations that include both, gas physics and dark matter, are required.

- how do galaxies obtain their gas?

  A recent study by Katz et al. (2002) suggested (somewhat radically) that in hydrodynamical simulations of galaxy formation most of the gas enters without ever heating to the virial temperature; the gas flow accretion is channeled along filaments and dominates at high-redshift. However, these findings are based upon SPH simulations and the authors themselves do not rule out numerical artifacts. Confirmation of these findings would be a natural by-product of the simulations already outlined in the previous point: in order to understand how the gas settles within the dark matter halo and forms a disk (mis-)aligned with the dark matter halo, it is important to keep track of the infall pattern and origin of the gas, respectively.

- where do the baryons reside?

  The density of baryons observed in stars and and gas in the local Universe does not exceed $\Omega_b \sim 0.01$ (Fukugita et al. 1998). Observations of the Lyα forest (Rauch et al. 1997) and the CMB (Spergel et al. 2003) give $\Omega_b \sim 0.04$. One possible explanation is that baryonic gas falls onto filaments where it is shock-heated forming the warm-hot intergalactic medium (WHIM). The existence of this putative WHIM is one of the most active areas in modern cosmology. Simulations which complement the new data being acquired by FUSE[19] and CHANDRA[20] are needed.

The run-time and analysis of high-resolution simulations that are able provide an insight into these problems will naturally take two years[21]. Not all of the simulations will be independent

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[19] `http://fuse.pha.jhu.edu/`

[20] `http://chandra.harvard.edu/`

[21] High-resolution simulations of this kind alone require of the order 50000 hours of dedicated CPU time using the latest generation of supercomputers (cf. Moore et al. 1999b).

and the projects are certainly entangled, respectively. Moreover, the whole AMIGA project is not rigorously fixed at three years code development and two years applying the code to astrophysical problems, which would even add up to five years rather than four; both the "technical" and the "physical" aspect of this application are obviously interleaving and already along the line of code development there will be important science output and some of the projects proposed in Section 1.3.3 do not rely on the final product at all. That makes it feasible to address all of them within the proposed time frame of four years.

Tackling above stated questions will not only provide us with a deeper understanding of the nature of our Milky Way and the Universe, respectively, but also make it possible to train PhD students in Computational Cosmology. The role and involvement of PhD students will be elaborated on in more detail in Section **??**, however, the idea for PhD students is to engage themselves in astrophysics rather than code development. The code development will mainly be addressed by myself leaving enough space for students though to gain sufficient numerical experience. This approach already worked very well for my current PhD student, Stuart Gill, who wrote a new halo finding algorithm for cosmological simulations based upon the hierarchical grid structure of `MLAPM`. He then used this piece of (highly non-trivial) software to investigate the dynamics of satellite galaxies in dark matter host halos. In the end, he wrote several conference proceedings and is (co-)author on four refereed journal articles and has simultaneously acquired the necessary numerical skills to fully understand and improve the N-body code `MLAPM`.

1.3.4 SUMMARY

A plan has been laid out illustrating how to augment the already functional and highly competitive N-body code `MLAPM` with all the necessary physics to model baryonic processes. Moreover, a detailed description of astrophysical applications has been provided showing that already along the lines of code development great strides towards a better understanding of the formation of our Milky Way and galaxy formation in general can be made. The proposed time frame of four years in total appears to be reasonable and during that time there is even enough room to train PhD students in a research field that will have a major impact on astronomy for decades to come.

2 CHOICE OF HOST INSTITUTION

The Astrophysikalisches Institut Potsdam (AIP) provides a natural environment for conducting the research and code development laid out in this application. The staff consists of world leading experts in the field of modeling galaxy formation and evolution self-consistently within the cosmological framework. This will be of a clear benefit to the success of this proposed project.

The AIP is actively involved in the RAdial Velocity Experiment (RAVE[22]) project. In fact, the science working group is chaired by Matthias Steinmetz, the director of the AIP. RAVE is an ambitious program to conduct an all-sky survey to measure the radial velocities, metallicities and abundance ratios of 50 million stars. This survey would represent a giant leap forward in our understanding of our own Milky Way galaxy, providing a vast stellar kinematic database three orders of magnitude larger than any other survey proposed for this coming decade. RAVE will

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[22] `http://www.aip.de/RAVE`

offer the first truly representative inventory of stellar radial velocities for all major components of the Galaxy. And as more than one of the (major) science cases laid out in this application in Section 1.3.3 are to decipher and disentangle the interplay of tidal debris associated with disrupting satellites galaxies and the Milky Way's dark matter host halo, it only seems natural to conduct such research "in-house". The theoretical models based upon the high-resolution simulations described here are then to be used to understand the RAVE observations and in turn gauge the parameters of the models.

Moreover, the AIP hosts (possibly) the largest supercomputer facility *solely* dedicated to astrophysics in the world. Their Beowulf cluster "Sanssoucci" consists of 135 Linux PC's with each of these PC's hosting two CPU's. The total memory capacity is an astonishing 600GB. Such a machine is more than well suited for increasing the number of particles used to "sample the Universe" by more than an order of magnitude and pushing those simulations to the foremost frontier of this kind of research, respectively. The whole system was installed just recently which guarantees the latest technology even in the very important networking connections between those PC's. It therefore only appears sensible to tackle state-of-the-art code development like the one described in this application at such an institute. Only dedicated access to supercomputers like the one at the AIP enables one to not only perform the highest resolution simulations of the formation of galaxies self-consistently, but also guarantees room for testing and benchmarking the code thoroughly.

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