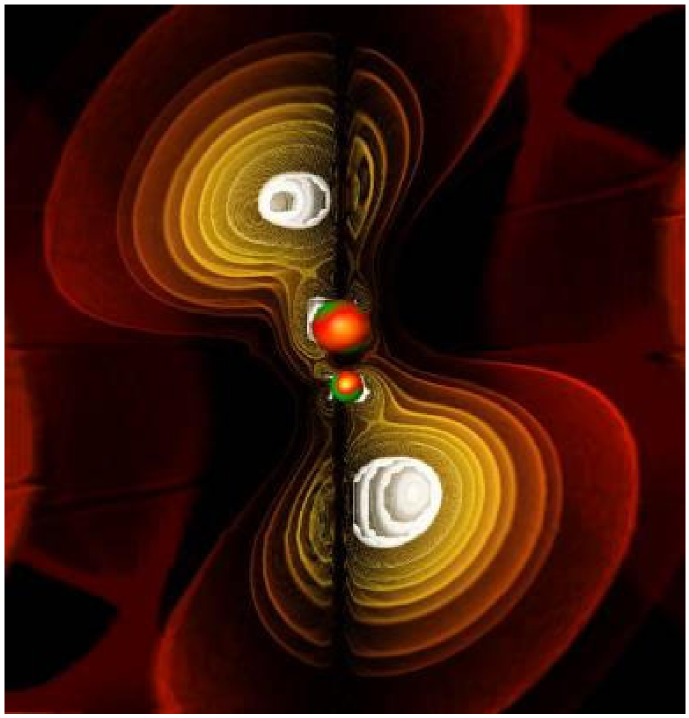
EU NETWORK
THEORETICAL FOUNDATIONS
OF SOURCES FOR GRAVITATIONAL WAVE ASTRONOMY
NEWSLETTER



Contents

1 EDITORIAL

The EU Network *Theoretical Foundations of Sources of Gravitational Wave Astronomy* is at the beginning of its second year, and it is time to summarize the most interesting results obtained by the collaboration. The goal of this first issue of the Newsletters is “to break the ice”, briefly resuming the results of the different groups, and to provide the bibliography for those who may be interested in more details.

This is only the starting point: I hope very much that the Newsletters will be used in the future not only as a mean to inform about one’s group activity, but also to discuss, and exchange ideas. I think it may also be useful to have a release of the Newsletters after the meetings we periodically organize, with reports on the highliths emerged from the discussions, and written version of the talks presented by students and postdocs.

In addition, I strongly encourage people, especially young people, whose scientific training is the main purpose of this collaboration, to write short reports on the results they obtain, even if they are at a preliminary stage: this will certainly make our collaboration more stimulating and fruitful.

Valeria Ferrari

2 AEI

Highlights of work in the AEI Group

The AEI Network node has many groups participating in the EU Network project. Scientific staff directly involved include Peter Diener, and Ed Seidel, and administrative staff include the AEI Scientific Coordinator Elke Mueller and EU Project Secretary Elke Geisler. Advisory Board member Bernard Schutz is an AEI Director, and another member, Sathyaprakash, is now visiting AEI for the 2001-2002 academic year. Many other members of the AEI numerical relativity group are involved in work related to the project: senior staff Miguel Alcubierre, Gabrielle Allen, and Bernd Bruegmann, postdocs Manuela Campanelli, Scott Hawley, Carlos Lousto, and Denis Pollney. John Baker recently left for a postdoc at NASA. New postdocs joining the group this fall include Francisco Guzman from Mexico, a scalar field expert, Keisuke Taniguchi recently from Meudon, an expert in binary NS initial data, and Ian Hawke from Cambridge, an expert in hydrodynamic methods and scalar fields. Research Programmer David Rideout, who just got his PhD in relativity, just joined the Cactus group and will be especially involved in helping EU Network folks on Cactus issues. PhD students: Tom Goodale continues work on methods for hyperbolic systems in relativity, Michael Koppitz works on black hole initial data and evolutions, Werner Benger and Ralf Kaehler continue work on advanced visualization techniques for relativity, and Ryoji Takahashi just left to join Novikov's group in Copenhagen. A new student, Frank Hermann, has joined to pick up on black hole evolutions.

In what follows, we focus on the work on Einstein equation evolutions, carried out by the AEI group, that are most relevant for the Network. In addition to what is described below, we have had a significant program in computational science, developing the Cactus Framework, that will be of great use to the Network. We have also worked on self-gravitating scalar fields, which will be reported elsewhere, and also on GR hydrodynamics, that has been covered in the SISSA and Thessaloniki reports.

General Development of the Einstein Equations for Numerical Relativity

Formulations and Reformulations of the Einstein Equations

We have spent much effort on understanding and developing treatments of computational general relativistic astrophysics for more stable and accurate evolutions of strongly gravitating systems. This includes different formulations of the Einstein equations, ways to handle the gauge degrees of freedom, including both the time slicing and the spatial coordinates, von Neumann stability analysis of the Einstein equations, and residual studies in its numerical solutions. These efforts have resulted in many improvements to numerical evolutions of Einstein's equations, that are available to—and should really aid—the entire Network effort in full scale nonlinear evolutions of all systems of interest: BH, NS, and Gravitational Waves.

First order hyperbolic systems have been favored as the most attractive way to formulate the Einstein equations for numerical studies, due to their clean mathematical structure. However, in most existing efforts, the numerical integration of these first order hyperbolic systems have not yet led to a substantial improvement over those using the traditional ADM evolution equations when carried out in full 3D.

In parallel with these developments, there have been various attempts to re-write the traditional ADM form of the evolution equations by separating out the conformal degrees of freedom. A recent reformulation of such an approach was introduced by Baumgarte and Shapiro, where it was shown that this new formulation leads to highly stable numerical evolutions. A detailed study of this approach using pure gravitational wave systems carried out by our group a couple of years ago confirmed that it has many advantages over the standard ADM formulation.

We studied and further developed this conformal approach, an effort that has been led by Miguel. Our improved formulations allowed far more stable evolutions than ever before, both with and without matter. With these improvements, for the first time we were able to simulate in full 3D the evolution of a gravitational wave so strong that it collapses to a black hole under its own self-gravity.

The above mentioned work in hyperbolic formulations and the conformal approach motivated us to develop a new formulation that contains both these elements: a formulation that separates out the conformal degrees of while requiring the remaining equations governing the non-conformal degrees of freedom to form a first order hyperbolic system. This work has not been applied to any large scale calculations yet.

New Gauge Conditions

The development of new classes of gauge conditions, including both the lapse function and the shift vector, and the implementation of older conditions in full 3D, such as the minimal distortion family of shift conditions, turns out to be critical to successful 3D evolutions. These conditions have brought about a marked improvement over our previous work, even the one just described above.

For the lapse, we have worked with both elliptic and hyperbolic conditions. The elliptic condition we use is the so-called "K-freezing" condition $\partial_t \mathrm{tr}K=0$. For initial data with $\mathrm{tr}K=0$ this condition reduces to the well known maximal slicing condition, but for $\mathrm{tr}K \neq 0$ is it more general.

The hyperbolic slicing conditions are based on the the Bona-Massó family of slicing conditions:

$$\partial_t \alpha = -\alpha^2 f(\alpha)\, \mathrm{tr}K \,. \tag{1}$$

We have found it useful, however, to modify this condition to

$$\partial_t^2 \alpha = -\alpha^2 f(\alpha)\, \partial_t \mathrm{tr}K \ . \tag{2}$$

Both conditions above lead to very similar hyperbolic evolution equations for the lapse. However, condition (2) has the advantage that it allows for static solutions even in the case in which $\mathrm{tr}K$ is not zero, which in turns allows the systems to settle to a stationary state at late times, once the true physical dynamics is over.

For the shift, we have experimented with families of elliptic, parabolic and hyperbolic conditions that relate the shift choice with the evolution of the conformal connection functions $\tilde{\Gamma}^i = \tilde{g}^{jk}\tilde{\Gamma}^i_{jk}$ that appear as independent variables in the formulation of Baumgarte and Shapiro. The elliptic shift condition is obtained by imposing that $\partial_t \tilde{\Gamma}^k = 0$. This results in a condition that is very similar to the minimal distortion condition known for years, but has excellent stabilizing properties and allows one to build in the condition at the analytic level by forcing the $\tilde{\Gamma}^i$ functions to be time independent. We further develop these conditions into parabolic and hyperbolic shift prescriptions by making either $\partial_t \beta^i$ or $\partial_t^2 \beta^i$ proportional to the elliptic operator given above. We call such conditions "driver" conditions.

We are presently working on a paper summarizing our results with these gauge conditions.

Black Hole Evolution Results

Our treatment of such problems is built on four independent components: new formulations of Einstein's equations, new gauge conditions, singularity excision techniques, and a hybrid nonlinear-perturbative technique known as Lazarus. This four-pronged approach to 3D black hole simulations has come together dramatically in the last year, improving by more than an order of magnitude the evolution times the community is capable of, and at the same time reducing numerical errors by large factors.

Grazing Black Hole Collisions

The first 3D grazing collision of two black holes of unequal mass, with spin and orbital angular momentum, was studied by Bruegmann, and was published just in 1999. That simulation was carried out with the standard ADM formulation, but no waveforms could be extracted and the code crashed already at $t \sim 7M$.

However, with the new formulations of the evolution equations discussed above, we were able to carry out simulations far beyond (over 5 times longer) what was possible before. These formulations, coupled with access to much larger machines that have recently become available, enabled us to carry out the most advanced 3D grazing BH collisions to date, including a detailed physics analysis. The collision can be followed through the merger to form a single BH, and through part of the ringdown period of the final BH.

We were able to compute gravitational waveforms for a grazing collision through fully nonlinear evolutions. The waveforms have an observed period and damping time consistent with a final distorted Kerr BH with $a/M = 0.7$, computed from the initial data. To achieve such a result, the resolution must be quite high (using grids of 387^3). We were also to use the waveforms to distinguish between different starting conditions having different physics parameters in full 3D black hole binary merger simulations. The apparent horizons were also tracked and studied, and physical parameters, such as the mass of the final BH, were computed. The total energy radiated in gravitational waves is shown to be consistent with the total mass of the spacetime and the final BH mass. We will push these simulations hard to explore the parameter space of 3D colliding black holes.

As we show below, by using new gauge conditions, excision, and hybrid perturbative/nonlinear evolutions (Lazarus) we expect to be able to significantly improve on these results this year.

New Singularity Excision Techniques

We haves devoted significant effort to "apparent horizon boundary condition" (AHBC) or "singularity excision" techniques for evolving black holes. Because the region of spacetime inside a black hole horizon cannot causally affect the region of interest outside the horizon, the interior domain containing the singularity can be cut away with a suitable boundary condition based on the use of the shift vector, and the use of a differencing scheme that respects the causal structure.

A new excision technique was developed at AEI, called "simple excision", where the different elements of the excision algorithm have been simplified as much as possible. This excision method is based on the following ideas: (a) Excise a *cube* contained inside the AH that is well adapted to cartesian coordinates; (b) Use a simple boundary condition at the sides of the excised cube: copying of time derivatives from their values one grid point out along the normal directions; (c) Use centered (non-causal) differences in all terms except for advection terms on the shift (terms of the form $\beta^i\partial_i$). For these terms we use second order upwind along the shift direction.

Very recent results, building on the simple excision technique, but now using the sophisticated new class of gauge conditions described above, show the remarkable improvement one can obtain by putting all these techniques together. We have shown how one can combine excision and the new gauge conditions to drive highly distorted, rotating black holes to an almost static state at late times, with well behaved metric functions. It is also shown for the first time that one can extract accurate waveforms from these simulations, with the full machinery of excision and dynamic gauge conditions. These evolutions can be carried out for long times, far exceeding the longevity and accuracy of even better resolved 2D codes. Furthermore, waveforms are also improved with this technique.

In summary, our excision techniques are very effective and robust, and verified to be correct through careful comparisons with perturbative and 2D nonlinear simulations from independent codes. These techniques will be applied to the more general case of binary inspiral in the coming year.

New Numerical/Perturbative Techniques

A hybrid nonlinear-perturbative technique is the so-called Lazarus project that is now providing some of the first predictions of waveforms from BH binary initial data in the innermost stable circular orbit (ISCO). In this approach we provide an interface between full numerical evolutions, which typically are rather short lived for general binary black hole data, and a perturbative evolution code. The basic idea is to evolve fully numerically (FN) until a final black hole has formed that can be treated as a Kerr black hole plus perturbation in the close limit approximation (CL).

As a first step we were able to extract a complete waveform from the head-on collision of black holes in 3d. We evolved Einstein's equations numerically from Misner initial data for several different initial separations. We then continued the evolution using a linearized treatment, following the Teukolsky equation. While the close limit, full numerical 2D, and our hybrid treatment all agree very well for small initial proper separations $L/M < 3$, for larger separations the close limit and full numerical curves deviate considerably. The hybrid results follow quite precisely the $2D$ computations. A minimal full numerical evolution time is essential in obtaining the above agreement.

In a recent paper we reported on the extension of this approach to rotating black holes, in particular to the plunge of two black holes from the ISCO, as defined by Baumgarte. In this case, we were able to compute the first waveforms from orbiting black hole initial data, which is only possible after some evolution with a full 3D numerical code, bring these data to the linear regime.

This hybrid nonlinear/perturbative technique will be applied to a more extensive set of fully nonlinear simulations that carry the various ISCO data sets (Baumgarte style and also recent data from the Meudon group) to a point where they can be evolved further with perturbative techniques this year, as proposed below. These calculations will provide detailed and convergent waveforms from initial data that are much closer to astrophysically relevant systems than ever before.

New Types of Binary Black Hole Initial Data

We are at present pursuing several different approaches to solving the initial value problem for binary black hole systems to see if we can make the initial data more astrophysically realistic than the conformally flat, Bowen-York extrinsic curvature puncture data we are using now.

Binary Black Holes in Circular Orbits

We are attempting to use the initial data provided by the Meudon group. These are based on the assumption of the existence of an helical Killing vector, representing a quasi-stationary spacetime describing binary black holes in circular orbit. The 3-metric is still conformally flat, but the extrinsic curvature is significantly different from the puncture data. The main problem in using these data, is that data is only provided outside of the apparent horizons, so filling up data in the interior is required for numerical evolutions. The main person working on this at the AEI is Michael Koppitz.

Kerr-Schild black holes

We are also working on implementing initial data based on the superposition of two Kerr-Schild black holes as proposed by Matzner, Huq and Shoemaker. These data are not conformally flat and the extrinsic curvature is different enough that the data as a whole should contain less spurious radiation than the puncture data. This is definitely true for a single boosted black hole, since the boosted Kerr-Schild data is still an exact solution. There are two parallel approaches to Kerr-Schild data. The first is spearheaded by Michael Koppitz and Denis Pollney, working within the framework of Cactus. The second is lead by Peter Diener using an Adaptive Mesh Refinement (AMR) package written by Alexei Khokhlov, that at present is outside of Cactus. However, a Cactus driver for this AMR package is currently under development.

Post-Newtonian initial data

Finally we are also working on Post-Newtonian initial data. These should have the advantage of being very good away from the black holes, but needs to be modified significantly near the black holes. We are currently investigating a 3-metric and extrinsic curvature provided by Gerhard Schäfer, Guillaume Faye and Piotr Jaranowski to build up an understanding of the behavior of the different terms in order to figure out how to solve the constraints. This work is done at the AEI by Manuela Campanelli, Wolfgang Tichy and Peter Diener with help from Denis Pollney and Bernd Brügman. We are also looking into the method proposed by Kashif Alvi, where the Post-Newtonian metric is glued together with tidally distorted black hole metrics in some interface regions by asymptotic matching. This is done in collaboration with Nina Jansen at the Theoretical Astrophysics Center in Copenhagen.

Significant Science Publications by the group in the last three years (2000-now).

Here we include a list of significant science papers published in research journals from 2000 to now.

1. M. Alcubierre, G. Allen, B. Brügmann, G. Lanfermann, E. Seidel, W.-M. Suen, and M. Tobias. Gravitational collapse of gravitational waves in 3d numerical relativity. *Phys. Rev. D*, 61:041501, 2000.

2. M. Alcubierre, G. Allen, B. Brügmann, E. Seidel, and W.-M. Suen. Towards an understanding of the stability properties of the 3+1 evolution equations in general relativity. *Phys. Rev. D*, 62:124011, 2000.

3. M. Alcubierre, W. Benger, B. Brügmann, G. Lanfermann, L. Nerger, E. Seidel, and R. Takahashi. The 3d grazing collision of two black holes. 2000. gr-qc/0012079, *Phys. Rev. Lett.*, in press.

4. M. Alcubierre, S. Brandt, B. Brügmann, C. Gundlach, J. Massó, and P. Walker. Test-beds and applications for apparent horizon finders in numerical relativity. *Class. Quant. Grav.*, 17:2159–2190, 2000.

5. M. Alcubierre and B. Brügmann. Simple excision of a black hole in (3+1)d numerical relativity. *Phys. Rev. D*, 63:104006, 2001.

6. M. Alcubierre, B. Brügmann, T. Dramlitsch, J.A. Font, P. Papadopoulos, E. Seidel, N. Stergioulas, W.-M. Suen, and R. Takahashi. Towards a stable numerical evolution of strongly gravitating systems: The conformal treatments. *Phys. Rev. D*, 62:044034, 2000.

7. Miguel Alcubierre, Bernd Brügmann, Denis Pollney, Edward Seidel, and Ryoji Takahashi. Black hole excision for dynamic black holes. *Phys. Rev. D Rapid. Comm.*, submitted, gr-qc/0104020.

8. G. Allen, T. Dramlitsch, T. Goodale, G. Lanfermann, T. Radke, E. Seidel, T. Kielmann, K. Verstoep, Z. Balaton, P. Kacsuk, F. Szalai, J. Gehring, A. Keller, A. Streit, L. Matyska, M. Ruda, A. Krenek, H. Frese, H. Knipp, A. Merzky, A. Reinefeld, F. Schintke, B. Ludwiczak, J. Nabrzyski, J. Pukacki, H-P. Kersken, and M. Russell. Early experiences with the egrid testbed. In *IEEE International Symposium on Cluster Computing and the Grid*, 2001.

9. J. Baker, S. R. Brandt, M. Campanelli, C. O. Lousto, E. Seidel, and R. Takahashi. Perturbative evolution distorted black holes. ii: Odd-parity modes. *Phys. Rev. D*, 62:127701, 2000. gr-qc/9911017.

10. J. Baker and M. Campanelli. Making use of geometrical invariants in black hole collisions. *Phys. Rev. D*, 62:127501, 2000.

11. John Baker, Bernd Brügmann, Manuela Campanelli, and Carlos O. Lousto. Gravitational waves from black hole collisions, by eclectic computation. *Class. Quant. Grav.*, 17:L149, 2000.

12. John Baker, Bernd Brügmann, Manuela Campanelli, Carlos O. Lousto, and Ryoji Takahashi. Plunge waveforms from inspiralling binary black holes. 2001. gr-qc/0102037.

13. John Baker, Manuela Campanelli, and Carlos O. Lousto. The lazarus project: A pragmatic approach to binary black hole evolutions. gr-qc/0104063, 2001.

14. S. Brandt, J. A. Font, J. M. Ibáñez, J. Massó, and E. Seidel. Numerical evolution of matter in dynamical axisymmetric black hole spacetimes. i. method and tests. *Comp. Phys. Comm.*, 124, 169-196, 2000.

15. B. Brügmann. Numerical relativity in 3+1 dimensions. *Ann. Phys. (Leipzig)*, 9:227–246, 2000. gr-qc/9912009.

16. Manuela Campanelli, Roberto Gomez, Sascha Husa, Jeffrey Winicour, and Yosef Zlochower. The close limit from a null point of view: The advanced solution. 2000. gr-qc/0012107.

17. Manuela Campanelli, Gaurav Khanna, Pablo Laguna, Jorge Pullin, and Michael P. Ryan. Perturbations of the kerr spacetime in horizon penetrating coordinates. *Class. Quant. Grav.*, 2000. gr-qc/0010034.

18. J. A. Font, M. Miller, W. M. Suen, and M. Tobias. Three dimensional numerical general relativistic hydrodynamics i: Formulations, methods, and code tests. *Phys. Rev. D*, 61:044011, 2000. gr-qc/9811015.

19. Jose. A. Font, Tom Goodale, Mark Miller, Luciano Rezzolla, Edward Seidel, Nikolaos Stergioulas, Wai-Mo Suen, and Malcolm Tobias. Three-dimensional general relativistic hydrodynamics ii: Long-term dynamics of single relativistic stars. *Phys. Rev. D*, 2001. to appear.

20. Carlos O. Lousto. Pragmatic approach to radiation reaction in binary black holes. *Phys. Rev. Letters*, 84:5251, 2000. gr-qc/9912017.

21. Carlos O. Lousto. Perturbative evolution of nonlinear initial data for binary black holes: Zerilli vs. teukolsky. *Phys. Rev.*, D63:047504, 2001.

22. Carlos O. Lousto. Towards the solution of the relativistic gravitational radiation reaction problem for binary black holes. *Class. Quantum Grav.*, 18, 2001. gr-qc/0010007.

23. Edward Seidel. Black hole coalescence and mergers: Review, status, and "where are we heading?". *Prog. Theor. Phys. Suppl.*, 136:87, 2000.

3 JENA

Analytical gravitational-wave inspiral

In OP-FSU collaborative work [1], the presently best analytical orbital phase expression of an inspiraling compact binary emitting gravitational waves has been obtained for quasi-circular orbits. The result still contains two unknown constants, a first one which comes from the emission process, and a second one which stems from the stationary orbital dynamics at the 3rd post-Newtonian order. In spite of this ambiguity, the found analytical phase expression should prove very useful for comparison with corresponding numerical simulations.

[1] L. Blanchet, G. Faye, B. Iyer, B. Joguet, "Gravitational-wave inspiral of compact binary systems to 7/2 post-Newtonian order"; prepr. gr-qc/0105099

Simplifying functional contact transformation

In a 1997 paper, Luc Blanchet (member of the Meudon knot) has given the gravitational radiation damping metric potentials to the 3.5 post-Newtonian order (this level is also called the first post-Newtonian radiation damping level since damping starts at the 2.5 post-Newtonian order) in a more compact form, but involving up to seven successive time derivatives of the multipole moments. The latter makes the expressions unmanageable for numerical implementations in extended matter (fluid) simulations. More recently, Luciano Rezzolla (member of the Trieste knot) et al. succeeded in simplifying the (mass-) current quadrupole part (appearing the first time at 3.5 post-Newtonian order) by a specific change of the coordinate system. In that way, the fifth time derivative of the mass-current quadrupole was reduced to its fourth derivative, whereby three more time derivatives could be eliminated by means of the continuity equation and the equations of motion without significantly reducing the numerical accuraracy. The full content of the mentioned change of coordinate system on the metric has been achieved by explicitly solving the field equations.

In the method developed by the Jena knot, the change of the metric needed for numerical applications can be obtained without solving the field equations, and the obtained functional contact transformation applies equally well to the much more involved change of the mass quadrupole part of the metric, as well as to the mass octupole part.

Non-conformally flat initial data set for binary neutron stars

Conformally flat initial data sets are extensively used in numerical simulations of inspiraling binary neutron stars, although those initial conditions do not allow to control incoming gravitational radiation. By the aid of the Jena knot, the first correction to conformal flatness has been obtained in a form that is useful for numerical implementation. The derived expression actually accounts for the no-incoming radiation condition to leading (post-Newtonian) order.

Post-Newtonian Theory

Research work is devoted to the following topics:

I. Reformulation of first post-Newtonian analytical GW wave form expressions, useful for numerical calculations

The first post-Newtonian analytical gravitational wave form expression is given fully generally in Blanchet et al. (1992), eq. (6.8). This expression contains time derivatives of multipole moments up to the fourth order. Higher order time derivatives are unmanageable in numerical simulations.

The time derivatives of the multipole moments were eliminated by repeated use of Newtonian and first post-Newtonian mass conservation equations and equations of motion. The resulting expressions contain new compact support Poisson integrals and, at most, second order space derivatives.

II. Derivation of first post-Newtonian radiation damping in a form useful for numerical implementations

A) *The Newtonian radiation damping, only showing the Newtonian mass quadrupole in a form useful for numerical implementations, is given in a 1992 paper by Blanchet et al. The current quadrupole part of the first post-Newtonian radiation damping, in a form useful for numerical implementations, was derived by Rezzolla et al. (1999).*

The much more complicated first post-Newtonian mass quadrupole part of the first post-Netonian radiation damping, as well as the Newtonian mass octupole part, were treated by the Jena knot by performing the following steps:

i) For fluids, we derived at 3.5 post-Newtonian order (first post-Newtonian radiation damping order) an infinitesimal functional coordinate transformation.

ii) By applying this transformation we obtained the Rezzolla et al. (1999) result, eq. (55), also starting from Blanchet (1997), eq. (3.6b), in a straightforward manner.

iii) The application of our new transformation to the Blanchet (1997), eqs. (3.6a), (3.6b), expressions, using Schäfer (1983), eqs. (4a), (4b), (6a), (6b), resulted in going from the seventh time derivatives of the mass quadrupole and octupole moments down to their fifths time derivatives. Up to the fourth time derivatives we succeded as in case of the wave form calculations. The one remaining time derivative seems to be best performed numerically

B) *The ADM formalism automatically results in first order in time evolution equations. The metric coefficients, at 3.5 post-Newtonian order, a priori contain second order time derivatives of the fluid variables, cf. Jaranowski and Schäfer (1997). The structure of the 3.5 post-Newtonian time evolution of the metric and the fluid can be found in Schäfer (1989) and (1990).*

The Jena knot computed the radiative part of the metric at the 3.5 post-Newtonian order for the case of perfect fluids in ADM coordinates. The result of Jaranowski and Schäfer (1997) for the space metric, obtained for the case of N gravitating point masses, was extended by accounting for internal energy and pressure terms. The lapse and shift function were determined at the corresponding order. The 3.5 post-Newtonian contributions could be rewritten in terms of Poisson integrals of regular sources involving compact support integrands for most of them. The transverse trace-free part of the spatial metric h_{ij}^{TT} was put under the same form as all the other integrals. Such an expression should prove useful to formulate a numerical initial value problem in the case of binary neutron star evolution since h_{ij}^{TT} represents the first correction to conformal flatness and, to leading post-Newtonian order, correctly takes into account the no-incoming radiation condition.

III. **Numerical implementation of the above as a module in Cactus, including advanced equations of state, to study the collapse of rotating evolved stellar cores, and the initial stages of merging NS binaries**

Cactus-training is ongoing. Implementation of the expressions discussed above has still to be done.

IV. Reformulation of the fully relativistic initial value problem to account for post-Newtonian physics input

Based on the papers by Schäfer (1985) and Jaranowski and Schäfer (1998) explicit analytical expressions have been derived to be applied in fully relativistic numerical initial value problem simulations for binary black holes.

V. Improved analytical treatments of inspiraling point-like binaries

In OP-FSU collaborative work [1], the presently best analytical orbital phase expression of an inspiraling compact binary emitting gravitational waves has been obtained for quasi-circular orbits. The result still contains two unknown constants, a first one which comes from the emission process, and a second one which stems from the stationary orbital dynamics at the 3rd post-Newtonian order. Again in OP-FSU collaborative work [2], the latter constant was shown to be equivalent to a constant found by other authors by other means. The orbital phase expression is very important for its comparison with numerical simulations of inspiraling compact binaries.

[1] L. Blanchet, G. Faye, B. Iyer, B. Joguet, "Gravitational-wave inspiral of compact binary systems to 7/2 post-Newtonian order"; preprint gr-qc/0105099

[2] V. C. de Andrade, L. Blanchet, G. Faye, "Third post-Newtonian dynamics of compact binaries: Noetherian conserved quantities and equivalence between the harmonic-coordinate and ADM-Haniltonian formalism", Class. Quant. Grav. **18** (2000) 753; preprint gr-qc/0011063

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G. Schäfer, *Higher-order post-Newtonian hydrodynamics*, in: Proceedings of the Fifth Marcel Grossmann Meeting on General Relativity, eds. D.G.Blair and M.J. Buckingham, World Scientific, Singapore, p. 467 (1989)

G. Schäfer, *Reduced Hamiltonian formalism for genera-relativistic adiabatic fluids and applications*, Astron. Nachr. **311**, 231 (1990)

4 PORTSMOUTH

The Portsmouth team and organizational developments

The numerical relativity group at Portsmouth has been in operation for two years and the EU network activities are playing a central role in its research effort. Members of the Portsmouth Relativity and Cosmology group actively participating in the Network are: Marco Bruni (lecturer), Andrea Nerozzi (Ph.D. student), Philippos Papadopoulos (lecturer), Carlos Sopuerta (TMR Fellow). In addition, Virginia Re, Uli Sperhake and Florian Siebel (students from the Salerno, Southampton and Garching groups respectively), are working on joint projects with members of the group.

Andrea Nerozzi has joined the group as of September 1, 2001, using the EU network founding. A second student (Virginia Re) has joined the group through a Ph.D. program funded by the Italian government. Computer resources are available through the Relativity and Cosmology group in the form of a workstation and network facilities. A Nuffield grant has been used to purchase an entry level parallel processing facility dedicated to network science. A SRIF award to the Relativity and Cosmology group will provide both local and remote computing facilities which may be used, in part, for network science purposes.

Scientific highlights

The Portsmouth group is pursuing research in topics in numerical relativity, relativistic hydrodynamics and theoretical aspects of perturbation theory.

A powerful approach to numerical relativity is based on the use of light-like spacetime foliations. The successful, long term stable, evolution of vacuum dynamical spacetimes, using this approach, has focused current attention on astrophysical applications. In the first instance this required the development of appropriate hydrodynamical formulations and codes, which are now being applied in spherical and axisymmetric configurations. The approach is ideally adapted to systems of quasi-spherical topology and is characterised by simplicity and economy. Physical systems that have been explored so far include: dynamically accreting (growing) black holes [1], spherically symmetric neutron star spacetimes [2, 3, 6], axisymmetric neutron star spacetimes [7], and axisymmetric (vacuum) black hole spacetimes [5]. There is significant further scope for development and this direction will be pursued systematically in the future.

A new line of research is focusing on systems which are initially close to quasi-equilibrium. A judicious manipulation of the evolution equations permits the effective subtraction of balanced background terms, with significant increase in accuracy and stability. The concept has been illustrated in spherically symmetric neutron star configurations [8], and a framework for more general spacetimes has been worked out [5].

Research Training and Collaboration

Visits and collaboration

- U.Sperhake (Southampton) interacted with the Portsmouth group on a weekly basis.
- F.Siebel (Garching) visited the Portsmouth group during the periods of 08/04/01 - 28/04/01 and 28/01/00 - 30/07/00
- J.A.Font (Garching/Valencia) visited the Portsmouth group during 7-21 May 2000
- L.Rezzolla (SISSA) visited the Portsmouth group during 29 June - 1 July, 2000
- P.Papadopoulos visited Paris and interacted with the IHES and Meudon groups during 03/05/01 - 09/05/01. Multiple visits to the Southampton node.

Workshops

- **1st EU Network meeting and Cactus workshop**, Dec 7th - Dec 9th 2000, Golm/Germany. Attendance: Bruni, Germani, Papadopoulos, Siebel, Sperhake
- **2nd EU Network meeting**, July 2001, Thessaloniki/Greece Attendance: Sperhake

Conference Presentations

- F.Siebel, "Global simulations of neutron star spacetimes in one and two dimensions", Talk at the Numerical Relativity workshop in Ngonyama/South Africa, July 2001.
- F.Siebel "Null cone evolution of neutron stars and gravitational waves", Talk at GR16 in Durban/South Africa, July 2001.
- F.Siebel, "Characteristic numerical relativity applied to hydrodynamic studies of neutron stars", Talk at MG9 meeting in Rome/Italy, July 2000.
- C.Sopuerta, "Geometrodynamics on a background manifold", Talk at the Numerical Relativity workshop in Ngonyama/South Africa, July 2001.
- U.Sperhake, "A new numerical approach to radial oscillations of neutron stars", BritGrav meeting in Southampton/UK, Mar 27th - Mar 28th 2001
- U.Sperhake, "Non-linear radial neutron star oscillations", 2nd EU meeting in Thessaloniki/Greece, Jun 6th - Jun 10th 2001
- U.Sperhake, "Non-linear radial neutron star oscillations" GR-16 in Durban/South Africa, Jul 15th - Jul 21st 2001
- P.Papadopoulos, "Non-linear black hole oscillations", BritGrav meeting in Southampton/UK, Mar 27th - Mar 28th 2001

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[4] *"Non-linear harmonic generation in finite amplitude black hole oscillations"*. P.Papadopoulos, Submitted,
gr-qc/0104024

[5] *"Geometrodynamics with a background connection"*, P.Papadopoulos and C.Sopuerta, Submitted
gr-qc/0107051

[6] *"Scalar field induced oscillations of neutron stars and gravitational collapse"*, F.Siebel, J.A.Font and P.Papadopoulos, submitted,
gr-qc/0108006

[7] *Light-cone evolution of neutron stars and gravitational waves*, F.Siebel, J.A.Font, E.Mller and P.Papadopoulos, Proceedings of GR16, to appear. (2001)

[8] *"Non linear radial oscillations of neutron stars"*, U.Sperhake, P.Papadopoulos, and N.Anderson, Submitted

5 ROME

The Rome group consists of two faculty members (Valeria Ferrari and Omar Benhar), two postdocs (José Pons and Leonardo Gualtieri) and three Ph. D. students (Emanuele Berti, Giovanni Miniutti and Alessandro Nagar). Omar Benhar is involved, as a nuclear physicist, in the study of the dependence of the gravitational waves emitted by neutron stars on the high-density equation of state (EOS). José Pons is the EU funded postdoc who has joined the Rome group since March. Previously he has been working in issues related to formation of neutron stars, physics of neutron star interiors and relativistic hydrodynamics. Now he is actively cooperating with the other members of the group in developing codes to describe stellar perturbations and gravitational wave emission. Leonardo Gualtieri is an INFN postdoc. He has been working with us since his Laurea thesis on stellar perturbations, and during his Ph. D. he has also gained some expertise on string theory. He is now involved in the study of perturbations of rotating stars. Emanuele Berti is about to complete his Ph. D. and will join the Thessaloniki group in November as an EU postdoc. His Laurea thesis was concerned with the dependence of stellar quasi-normal modes on the equation of state. Then he studied the excitation of g-modes in Newtonian stars, and his Ph. D. thesis concerns the study of neutron-star binaries in a perturbative approach. Giovanni Miniutti has been working on black hole exact solutions in the $3+1$ formalism and black hole perturbations. He is now involved in the study of the g-modes in white dwarfs and neutron stars. He will finish his Ph. D. in October 2002. Alessandro Nagar, a Ph. D. student in Parma, is working with us on the perturbations of a collapsing fluid.

The main results obtained by the group in the first year of activity of the network and prospects for the next year are:

Relativistic stellar perturbations

We have integrated the equations describing a binary system revolving in an eccentric or circular orbit [2]. These equations have been derived by a perturbative approach in the frequency domain, assuming that one of the two objects is a point-like mass which induces a perturbation on the gravitational field and on the internal structure of the other. This approach constitutes a progress with respect to the commonly used assumption that both stars are point-like masses, since we treat at least one of the two stars, whose internal structure and whose gravitational field are solutions of the fully non-linear equations of gravity, in an exact manner.

We have applied this formalism to study the perturbations of a solar-type star excited by a close orbiting planet [1]. The integration has been performed in the frequency domain. We have computed the energy spectra of the radiation emitted in gravitational waves. The purpose of this study was to understand whether the extra-solar planetary systems that have recently been discovered in large number in our galaxy could be interesting sources of gravitational waves. These systems are of particular interest because they are very close (a few parsecs from Earth), and in some of them the planet is on such a narrow orbit that the frequency of emission could be in the bandwidth of the space-based interferometer LISA. In particular we have investigated the possibility that a planet is on an orbit so close that, without being disrupted by tidal forces, it may significantly excite the stellar g-modes. We find that gravitational emission is significantly enhanced if the planet is a brown dwarf, and in this case it could move on an orbit resonant with the mode g_4 of the star emitting radiation strong enough, and for a sufficiently long period of time, to be detectable by LISA.

We now plan to study the excitation of the g-modes of neutron stars and white dwarfs due to the interaction with an orbiting companion and evaluate the consequent gravitational emission. The excitation of neutron star g-modes may be interesting for VIRGO-LIGO, because the typical frequencies range within $\sim 100 - 400$ Hz, where the ground-based interferometers are most sensitive; the excitation of white dwarf g-modes may occur in close white dwarf binaries that are quite common in our Galaxy, and may be interesting for LISA.

In [2] we considered a neutron star perturbed by a point mass moving around it on a closed orbit; we found a beating effect between the ($\ell = 2$, $m = 2$) and the ($\ell = 2$, $m = 1$) gravitational-wave frequencies, which is clearly visible in the waveforms (figure 1) and is not predicted by the standard Post-Newtonian approach. We also found that the gravitational radiation the system emits in the $\ell = 2$ multipole is smaller than that predicted by the quadrupole formalisms, which takes into account only the radiation emitted because of the orbital motion; this effects is most significant when the two stars are close (orbital radius less than $\sim 10R_*$). The star we have used as a model has a polytropic equation of state $p = K\epsilon^n$, with $K = 100\ km^2$ and $n = 2$.

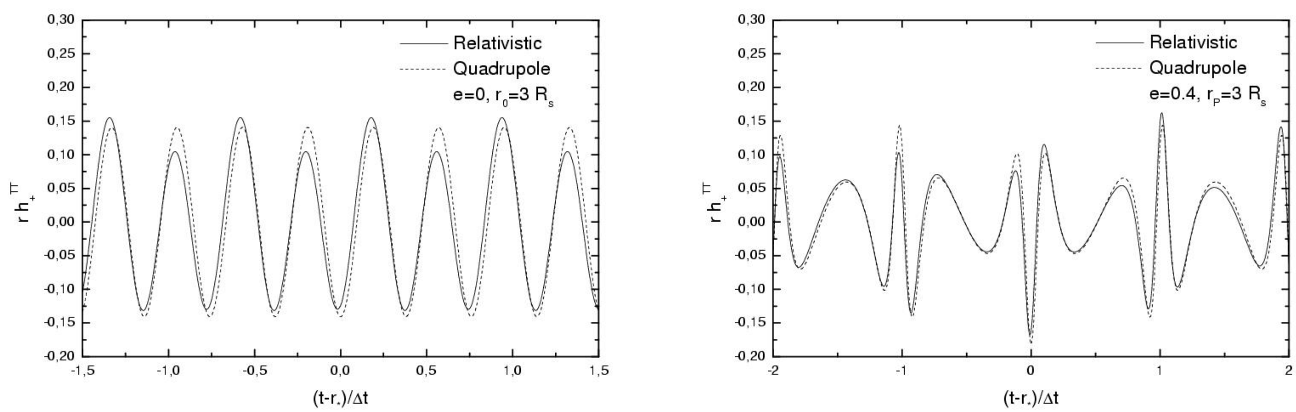

Figure 1: The h_+^{TT} component of the gravitational wave emitted when a test mass moves on a closed or quasi-periodic orbit is plotted versus the retarded time in units of the orbital period. Since we assume that the observer is on the equatorial plane, the $h_\times^{TT}$ component vanishes. The waveform on the left refers to a circular binary with $e = 0$ and $r_0 = 3R_s$, the one on the right to an eccentric binary with $e = 0.4$ and periastron $r_P = 3R_s$. The solid line corresponds to the relativistic waveform and the dashed line to the waveform computed by the quadrupole approach. Only the $\ell = 2$ component of the relativistic signal is shown.

This result affects the orbital evolution of the system, especially during the last phases of the coalescence of neutron star binaries, whose signal is considered as a target for the detection of gravitational waves by ground based interferometers (VIRGO-LIGO-GEO-TAMA). Therefore, we have included in our perturbation scheme the effects of radiation reaction, and we have studied the orbital evolution of the coalescing system and computed the waveform of the emitted gravitational signals. We plan to extend our investigation to understand to what extent this result depends on the equation of state and on the finite size of the star. We will study the role the EOS of neutron stars plays on the gravitational emission, by studying the possibility of characterizing the different EOS's through integral quantities (e.g. the speed of sound in matter integrated over the whole stellar volume), to circumvent the ambiguity arising from the density dependence of matter compressibility.

In order to be extracted from the unavoidable noise of a gravitational detector, the signals emitted by astrophysical sources have to be known with an extremely high accuracy. This is due to the fact that the matched filter which is used in the data analysis is very sensitive to a mismatch of the parameters, to such an extent that even a mismatch of one cycle over 10^4 in the signal produced during the coalescence of a binary system degrades the signal-to-noise ratio by a factor ~ 2. At present, templates for coalescing binaries can be generated either by our perturbative approach, or by the Post-Newtonian approach, therefore we will compare the waveforms we find with the waveforms predicted by the Post-Newtonian formalism and we shall evaluate the SNR of the matched-filter used to extract the signal from the detectors' noise in the two cases. As a preliminary result, in figure 2 we show the power emitted in gravitational waves (normalized to the quadrupole power) by a neutron star, a Schwarzschild black hole with the same mass and the Post-Newtonian approximation at several orders, in the test particle limit.

In collaboration with the group at the University of Thessaloniki, we are presently investigating the possibility of simulating the evolution of a binary system, as far as the emission of gravitational waves is concerned, as a process of scattering of the quadrupole wave emitted by one star, seen as an extended body in orbital motion around the other, on the potential barrier generated by the second star and viceversa. If this approach happens to be successful, we will be able to study the latest phases of the coalescence taking into account also the tidal deformations reciprocally induced by the interacting stars and the effects they produce on the emitted radiation.

Convective instabilities in proto-neutron stars

In a collaboration with professor Juan A. Miralles (U. de Alicante and U. de Valencia, Spain) and professor Vadim Urpin (IOFFE Institute of Saint Petersburg, now on sabbatical at the U. of Valencia), we have extended our previous work [6] to study the influence of magnetic fields on convective instabilities arising in newly formed neutron stars or proto-neutron stars. Our work (Miralles, Pons & Urpin, Ap. J., in preparation) shows that the convective instability, normally arising in all numerical simulations due the inverse entropy and lepton gradients in the shocked region of supernovae cores, is mostly suppressed with magnetic fields of order $\sim 10^{15}$ Gauss. This can be taken as an upper limit for the magnetic field of magnetars created by the standard mechanism of dynamo action in proto-neutron stars. The connection of convective instabilities and unstable g-modes of neutron stars is under study and will be addressed in forthcoming works.

Stochastic background

In collaboration with Sabino Matarrese (University of Padova) and Raffaella Schneider, in the past years we had developed a procedure to compute the spectral energy density and the strain amplitude of the background of gravitational waves produced by cosmological populations of astrophysical sources. This procedure is based on two ingredients: the knowledge of the star-formation rate history up to large cosmological redshift, which is derived by astronomical observations, and the energy spectrum emitted in gravitational waves by a specific source, which is derived by theoretical calculations. Using this approach, in the past year we have computed the characteristics of the background generated by various populations of compact binaries, composed of white-dwarfs, neutron stars, black holes, or mixed combinations of these objects. The formation and evolution of populations of binaries of different type has been taken into account by using the results of a population synthesis code

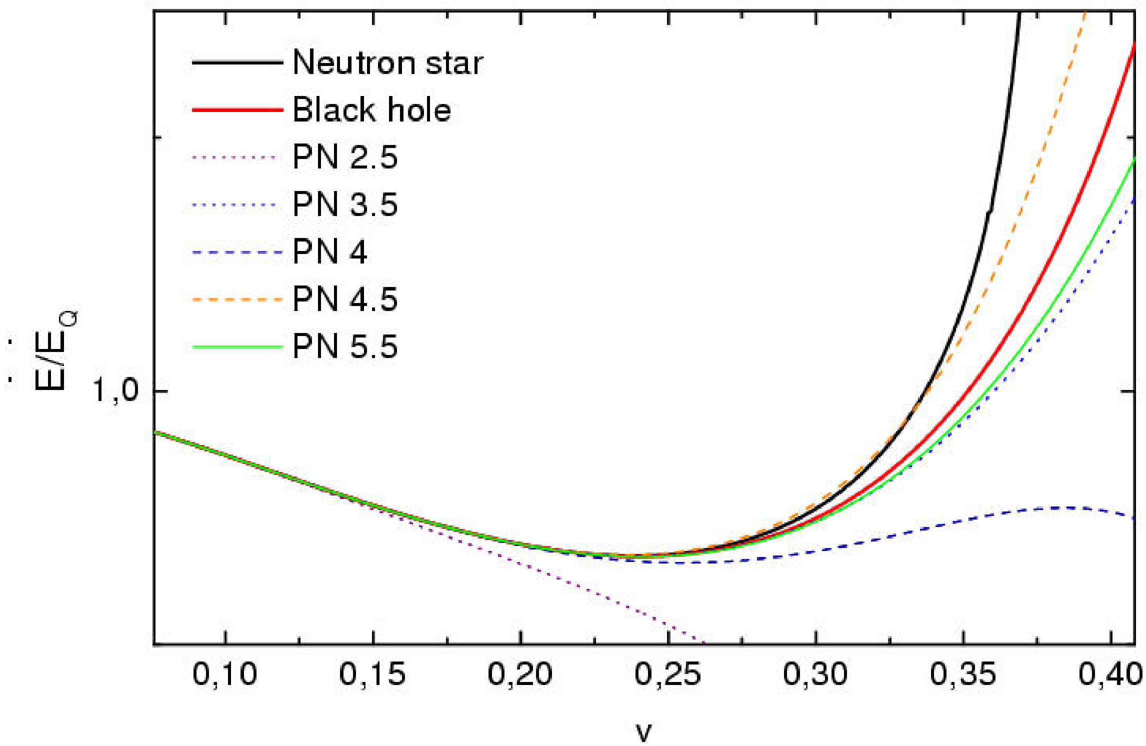

Figure 2: The power emitted in gravitational waves by a neutron star and a Schwarzschild black hole with the same mass perturbed by an orbiting massive test particle (both obtained summing multipoles from $\ell = 2$ to $\ell = 7$) is plotted as a function of the orbital velocity $v = (\pi M \nu_{GW})^{1/3}$, where ν_{GW} is the gravitational wave frequency. The power is normalized to the quadrupole emission. The results are compared with the predictions of the Post-Newtonian approximation at several orders in the test particle limit. The v-range is chosen so that the orbital frequency sweeps from 10 Hz, where the signal first enters the LIGO-VIRGO sensitivity window, to the ISCO. The post-newtonian expansion slowly converges to the Schwarzschild result, and the effects of the structure of the star on the energy output is quite clear.

elaborated by S.Portegies Zwart. We find that the extragalactic contribution of white-dwarf binary systems acts as a significant confusion-noise in the LISA bandwidth [3].

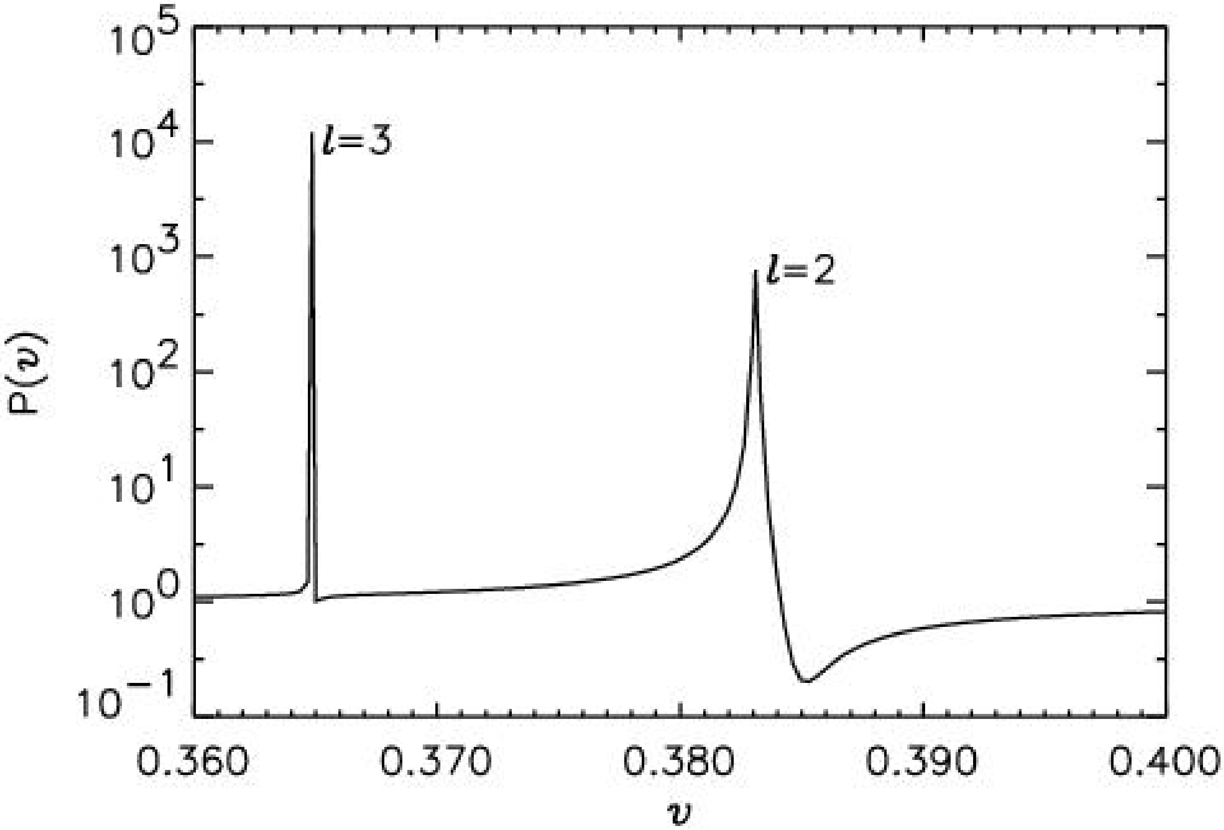

Figure 3: If we refine the calculations for the perturbed neutron star shown in figure 2 in the region $\upsilon > 0.35$, we find sharp peaks which correspond to the excitations of the **f**-mode of the star for $\ell = 2$ and 3. In this figure we plot the emitted power in that region. The frequencies of the modes are $M\omega_{GW} = 0.1125$ and $M\omega_{GW} = 0.1457$, respectively. The peaks for $\ell > 3$ are extremely sharp and can be seen only with an extremely high resolution.

Below we give the list of publications of the group's members since August 2000.

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6 SOUTHAMPTON

The first year of the European network for Gravitational wave sources has been an active one for the Southampton group. Combining the EU grant with several other grants, the group has four permanent members of staff and currently supports three postdocs and five research students.

The EU funded postdoc, Reinhard Prix, works with Nils Andersson and a PPARC funded postdoc Ian Jones on modelling various aspects of gravitational waves from neutron stars. The addition of Reinhard's expertise on relativistic superfluids has provided significant momentum in the direction towards more realistic models as most mature neutron stars are expected to have superfluid constituents. We were also strengthened by the fact that Greg Comer was able to visit from St Louis during two months of the summer. At the present time much of the foundation for understanding the dynamics of superfluid stars has been laid and we are moving towards studies of astrophysical problems. In a series of paper we have i) studied rotating two-fluid configurations in which the two fluids are allowed to rotate at different rates [1, 2] (recall that the standard model for neutron star glitches is based on transfer of angular momentum between two loosely coupled components), ii) investigated neutron star oscillation modes both qualitatively and in quantitative detail [3, 4]. So far the main new results concern the possible existence of two classes of r-modes (which may be unstable due to the emission of gravitational waves) in a superfluid star and progress in understanding the effect of entrainment (which couples the two fluids in a non-dissipative way) in relativistic oscillations. We are currently formulating the equations that describe inertial modes (of which the infamous r-modes is a subclass) in both a Newtonian and a relativistic context. We anticipate considerable progress in this area in the next year. Particularly fruitful may be a long-term visit of Reinhard to Toulouse and the group of Michel Rieutord, who has considerable expertise on the oscillations of rotating Newtonian stars. Reinhard is also involved in a collaboration with Jerome Novak (Meudon) and Greg Comer on developing a fully relativistic numerical code for determining rapidly rotating two-fluid configurations.

The groups work on the r-mode instability has continued apace. Results from the past year range from the first detailed study of the inertial modes of a relativistic star [5, 6] to phenomenological modelling of the astrophysical relevance of a strong instability in a newly born neutron star [7]. Together with Kokkotas, Andersson has written a major review article on the many aspects of the r-mode problem [8]. The groups main r-mode project is carried out by Ian Jones and is based on the idea of using perturbative time-evolutions to understand various aspects of a secular gravitational-wave instability. This programme was slightly delayed as papers on freely precessing neutron stars (an often mentioned, but rarely analysed in detail, source for gravitational waves) were written [9, 10] but good progress has still been made. In its current reincarnation, the numerical code preserves an r-mode oscillation for several hundred rotation periods of a rapidly spinning (and thus centrifugally deformed) Newtonian star. As one of the many code tests we have verified the mode frequencies calculated by Karino et al. This comparison shows that the numerical approach can provide results with excellent accuracy. In the near future we plan to extend the project in three important directions. First of all, Ian and Anna Watts will study the effect of differential rotation. Secondly, we will implement a local gravitational radiation reaction force according to the description of Blanchet, Damour and Schaefer. Here we will initially restrict the study to the mass multipole radiation (which although less important than the current multipole for r-modes is still significant), but the hope is that discussions with the Jena group will allow a definite prescription for including also current multipoles in a numerically accurate way. Finally, preliminary sketches have laid out a framework for extending the code to the weakly nonlinear regime. This would allow us to investigate the role of mode-coupling and perhaps also begin to probe mode saturation. All in all, it is anticipated that these steps will provide significant insight into the r-mode (and analogous) instabilities.

Together with Philippos Papadopoulos in Portsmouth (and to some extent Andersson), Uli Sperhake (who is due to defend his PhD thesis in October and then join the Thessaloniki group) has carried out detailed tests of a novel approach to nonlinear perturbation calculation. The idea is that one can in many quasistationary situations benefit from subtracting off a known "background" and focus attention of whatever is left — the "perturbations". The early studies have demonstrated the great promise of this scheme, with applications to neutron star oscillations and shock formation.

In addition to these main projects, the group has made some progress on perturbations of rotating black holes. Andersson has worked with Kostas Glampedakis in Cardiff on the late-time behaviour of perturbations of near extreme Kerr [11, 12], and Rhiannon Williams is developing a 2+1 null-timelike perturbation code. The hope is that this will provide a useful tool that will allow us to study the late-time behaviour in further detail. It is also possible that the approach can be extended to study rapidly spinning stars. This would be an important application and we intend to pursue the problem in the next year or so.

The progress on the Cauchy-Characteristic Matching project has been fairly limited because of personnel problems. It did not prove possible to recruit either a Network postdoc or a postgraduate student to work on the project. This only leaves Ray d'Inverno involved in code development, although he has made two visits to Golm to work on the code with Denis Pollney. Unfortunately, Ray has limited time to devote to the project because of his major administrative responsibilities as Deputy Dean in the Mathematics Faculty. An upto-date review of the current status of the code can be found in [13]. There is now a considerable body of evidence that CCM has distinct advantages in one dimensional problems i.e. those possessing cylindrical or spherical symmetry. However, it has not as yet proved itself in two dimensional problems i.e. axisymmetric systems. A master CCM vacuum code has been constructed which consists of four modules: a Cauchy interior module, a characteristic exterior module, an interface injection module and an interface extraction module. To date the Cauchy module has been tested and gives good results for Schwarzschild (where it runs stably for times in excess of 1000M), so-called eta waves and $l = 2$ and l=3 Teukolsky waves. Testing is currently focused on the characteristic module. The hope remains that if it proves possible to demonstrate that CCM still possesses advantages in two dimensions, then it will be a relatively easy process to extend the two dimensional code to three dimensions (where effectively the only difference is that the dependent variables will additionally become functions of the polar azimuthal coordinate ϕ.)

Carsten Gundlach and (EPSRC funded postdoc) José María Martín-García have informally joined the network to work on the perturbations of spherical stellar collapse. They have recently derived a general framework for evolving the non-spherical perturbations of a time-dependent spherical perfect fluid solution [14, 15]. It is similar to that of Ed Seidel's PhD thesis [16, 17], but formulated without reference to coordinates. We are now going to apply it to two types of gravitational wave source: the core collapse and bounce in a type II supernova, and the accretion-triggered collapse of a neutron star to a black hole. Originally, we are planning a free-standing code based on the Valencia collapse code, in collaboration with José Pons and Jerome Novak. Ed has also volunteered to put various background codes into Cactus, so that different background and perturbation codes can be combined. In preparation, we plan to write our code so that it accepts background data in any coordinate system. We would like input on interesting background physics and, even more importantly, suggestions for realistic initial data for the perturbations!

Outside the scope of the EU network, Carsten and José María are working on critical phenomena in gravitational collapse. Our current projects are collisionless matter and non-spherical perturbations of a perfect fluid. Is anyone looking for a nice 1D evolution warmup project for a graduate student? Carsten would like to test symmetry-seeking coordinates [18] in critical collapse, as a toy model for merging binaries, but lacks the time.

The network support has allowed us to increase our interaction with our European colleagues and exchange news and views in an unprecedented way. Particularly profitable has been the visits of several members of the SISSA and Meudon groups to Southampton, and the two network meetings in Golm and Thessaloniki. The fact that we could afford to bring most of our students to the latter two events was of major importance for the group. Several members of the group (Andersson, Jones and Sperhake) stayed in Thessaloniki after the June meeting and interacted actively with their group. In addition to this, the network funds enabled visits of Gundlach and d'Inverno to Golm and several visits of Prix to Paris.

We are currently planning a meeting in Paris during November or December 2001, in order to make further progress on the many aspects of stellar instabilities that are being investigated within the network. We are also looking forward to hosting the next network meeting in January or February 2002. Although we are unlikely to find a beach location that compares to Greece (and let's not even mention the food) we expect the meeting will still be an exciting event and we hope that all our network colleagues will enjoy a few rainy days on Britain's riviera.

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7 THESSALONIKI

Study of gravitational waves from stable/unstable neutron star models

We have studied large-amplitude nonlinear r-modes in rotating relativistic stars, performing time evolutions on dynamical timescales (using a code based on Cactus) [1]. These evolutions showed that r-modes do not saturate hydrodynamically at amplitudes of order unity. In addition, the existence of discrete r-modes in isentropic stars has been confirmed. New simulations are now being performed at amplitudes larger than unity, to determine the maximum saturation amplitude and to study the appearence of shocks. *Collaboration with Valencia.*

We obtained the first pulsation frequencies of quasi-radial modes in rapidly rotating relativistic stars, in full general relativity via nonlinear time-evolutions of appropriately perturbed initial data (using Cactus) [2]. With the same 3D nonlinear code we studied quadrupole pulsations of nonrotating relativistic stars, showing excellent agreement with linear perturbation results for the oscillation frequency and the extracted gravitational waveform. *Collaboration with AEI/Valencia/SISSA and WashU.*

We studied axisymmetric modes of pulsation of rapidly rotating relativistic stars (in the Cowling approximation) using a 2D nonlinear hydrodynamical code [3]. Pulsation frequencies for several f- and p-modes have been obtained even near the mass-shedding limit, where apparent mode crossings between different modes appear. These results (in the Cowling approximation) have served in validating corresponding results in 3D nonlinear evolutions [2]. *Collabration with Valencia.*

1. *Nonlinear r-Modes in Rapidly Rotating Relativistic Stars*, N. Stergioulas & J. A. Font, **Phys. Rev. Letters**, 86, 1148 (2001)

2. *Three-dimensional general relativistic hydrodynamics II: long-term dynamics of single relativistic stars*, J. A. Font, T. Goodale, S. Iyer, M. Miller, L. Rezzolla, E. Seidel, N. Stergioulas, W. Suen & M. Tobias, preprint (to be submitted to Phys. Rev. D), 2001

3. *Axisymmetric Modes of Rotating Relativistic Stars in the Cowling Approximation*, J.A. Font, H. Dimmelmeier, A. Gupta & N. Stergioulas, **MNRAS**, 325, 1463 (2001)

Further development of perturbative techniques to infer detailed information about GW sources i.e. mass, radius, rotational rate and, in the case of NS, the EOS of the final object.

We derived the linear perturbation equations governing oscillations of strongly magnetized relativistic stars, in the Cowling approximation [4]. For a simplified magnetic field configuration we computed the fundamental torsional mode frequency as a function of magnetic field strength. Torsional modes of strongly magnetized relativistic stars could be excited in Soft Gamma-Ray Repeater sources (SGRs) and, if detected, could provided clues about the high-density EOS.

We studied strange stars in LMXBs, finding limits on the maximum orbital frequency and comparing these to recent observations [5]. The maximum orbital frequency may be limited by secular and dynamical instabilities, during which GWs are emitted. *Collaboration with Meudon.*

The EOS of compact stars in some binary systems could be determined by long-term observations of the spin-down of binary pulsars. We derived a formula that would allow to constrain the EOS, when such observations become available [6].

4. *Torsional Oscillations of Magnetized Relativistic Stars*, N. Messios, D. B. Papadopoulos & N. Stergioulas, **MNRAS**, in press (2001)

5. *Lower Limits on the Maximum Orbital Frequency Around Rotating Strange Stars*, D. Gondek-Rosinska, N. Stergioulas, T. Bulik, W. Kluzniak & E. Gourgoulhon, **A&A**, in press (2001)

6. *Evolutionary Self-Energy-Loss Effects in Compact Binary Systems: Importance of Rapid Rotation and of Equation of State*, N. K. Spyrou & N. Stergioulas, **A&A**, 366, 598 (2001)

Development of perturbation equations for slowly rotating stars for numerical time evolutions. Generic initial data will then be evolved, with special focus on the various pulsation modes of the system.

We studied the time evolution of purely axial modes within the fully relativistic framework, using the slow rotation approximation. In a further approximation, the low frequency approximation, where the gravitational radiation is neglected, we showed both through mode calculations and time evolutions that the existence of the relativistic r-mode strongly depends on the stellar parameters, such as the equation of state and the compactness M/R [7], which is in clear contrast to the Newtonian theory, where r-modes always exist. Even with the inclusion of the radiation reaction, the picture does not change much, and r-modes can only exist for a limited class of stellar models [8].

When deriving the evolution equations for the polar perturbations of slowly rotating stars, the commonly used Regge–Wheeler gauge proved to be quite impractical. Only through the tedious process of combining and rearranging the perturbation variables in a clever way, it was possible to cast the equations into a form which is well suited for the numerical integration. Still, the equations remain quite lengthy and we therefore rederived the perturbation equations in a different gauge, which in the ADM formalism immediately yields a fairly simple hyperbolic first order set of equations [9].

7. *On the r-mode spectrum of relativistic stars in the low frequency approximation*, J. Ruoff & K. D. Kokkotas, **MNRAS**, in press, gr-qc/0101105 (2001)

8. *On the r-mode spectrum of relativistic stars: Inclusion of the radiation reaction*, J. Ruoff & K. D. Kokkotas, **MNRAS**, submitted, gr-qc/0106073 (2001)

9. *Evolution equations for the perturbations of slowly rotating relativistic stars*, J. Ruoff, A. Stavridis & K. D. Kokkotas, **MNRAS**, submitted, gr-qc/ 0109065 (2001)

10. *Oscillation and Instabilities of Relativistic Stars*, K. D. Kokkotas & N. Andersson, invited review for SIGRAV XIV, Genoa 2000, gr-qc/ 0109054 (2001)

8 VALENCIA

(A) The Valencia Team and Organizational Developments

The group of relativistic astrophysics in Valencia has been in operation since the end of 1980s. Current members of the group are: José M$^{\underline{\text{a}}}$. Ibáñez (Prof., Local Coordinator), Juan A. Miralles (Assoc. Prof., since October 2000 in the University of Alicante), Armando Pérez (Assoc. Prof.), José M$^{\underline{\text{a}}}$. Martí (Assoc. Prof.). Since the epoch the funded proposal was submitted, several changes in the composition of the group have taken place: two new doctoral students have joined the group: Luis Antón (Ph.D. program funded by the Spanish government) and Manuel Perucho (Ph.D. program funded by the University of Valencia). Joachim Frieben has joined the group as of June 1, 2001, using the EU network founding. José A. Font-Roda (a former doctoral student of the group) is also joining the group through a Marie-Curie return grant.

(B) Scientific Highlights

I. Numerical Relativistic Hydro(-Magneto)dynamics

The *exact solution of the Riemann problem (RP) with non-zero tangential velocities in relativistic hydrodynamics* has been obtained by Pons, Martí & Müller (see [7], [15]) by solving the jump conditions across the shocks plus an ordinary differential equation arising from the self-similarity condition along rarefaction waves. The knowledge of the exact solution of the RP allows one to derive an *exact Riemann solver* in the field of (multidimensional) relativistic hydrodynamics. This paper is a keystone in the way of generating multidimensional tests to be overcome by any multidimensional relativistic hydro-code (based on Riemann solvers or not).

In [6] we have explored the possibility of extending modern high-resolution shock-capturing (HRSC) techniques to the field of *radiative transfer*. A very interesting by-product of this analysis is the existence of constraints on the closure relation coming from the assumption of hyperbolicity.

We have started to build up a multidimensional *relativistic magnetohydrodynamic (RMHD)* code, based on HRSC techniques. Some preliminar results with a Newtonian version can be found in [9]. Currently, we have already developed a RMHD code for the particular case in which the magnetic field is assumed to be passive.

II. Hydrodynamical Simulations of Astrophysical Sources of Gravitational Radiation

In [8] we have analyzed the features of the gravitational radiation coming from a given spatial distribution of *galaxy clusters*. The simulations of the formation of an isolated galaxy cluster were made (in previous papers) using a 3D Eulerian code (for the baryonic component), which incorporates modern HRSC techniques, coupled –through Poisson's equation– to a N-body code (for the dark matter component).

With Dr. Novak (member of the Meudon node) we have studied [5] the collapse of a degenerate stellar core, within *tensor-scalar theory of gravity*, leading to the formation of a neutron star through a bounce and the formation of a shock. As a main result, we describe the resulting gravitational monopolar radiation (form and amplitude) and discuss the possibilitiy of its detection by the gravitational detectors currently under construction. As a by-product of this work, we have succeeded in building a hybrid code which couples the state-of-the-art of modern HRSC techniques and pseudo-spectral methods.

III. Simulations of relativistic flows

We continue working in our line of research concerning the study of relativistic flows in astrophysical systems such as: *extragalactic relativistic jets*, *relativistic jets from collapsars* and *accreting relativistic flows onto a black hole*. Although the two first topics are not directly related with the objectives of the network I consider that they might be of interest for some members of the network, at least from the point of view of the application of numerical techniques, in relativistic hydrodynamics (HRSC), which are also used, in their general-relativistic extension, by researchers in some of the nodes of the network.

III.1 Extragalactic relativistic jets

The first radio emission simulations from high-resolution three-dimensional relativistic jets have been presented in [1] and [10]. They have been generated running GENESIS, an optimized and parallelized 3D special relativistic hydro-code, which is suited for massively parallel computers with distributed memory. A general-relativistic version of GENESIS is currently in progress.

III.2 Relativistic Jets from Collapsars

In [2], [14] and [11] we have analyzed, in the framework of the theory of special relativity, the formation of Gamma-Ray Bursts according to the previous suggestions, in the Newtonian case, of MacFadyen & Woosley. Using a collapsar progenitor provided by MacFadyen & Woosley, we have simulated the propagation of an axisymmetric jet through a collapsing rotating massive star with GENESIS. The jet forms as a consequence of an assumed energy deposition in the range $10^{50} - -10^{51}$ ergs s^{-1} within a 30^0 cone around the rotation axis. The jet flow is strongly beamed, spatially inhomogeneous, and time dependent. Outside the star, the flow begins to expand laterally but the beam remains very well collimated. When the simulation ends, the Lorentz factor has increased up to 44.

III.3 Accretion onto a Black Hole

We have developed a numerical code to study the evolution of self- gravitating matter in dynamic black hole axisymmetric spacetimes in general relativity. In [3] we make some studies of the spherical and axisymmetric accretion onto a dynamic black hole, the fully dynamical evolution of imploding shells of dust with a black hole, the evolution of matter in rotating spacetimes, the gravitational radiation induced by the presence of the matter fields and the behavior of apparent horizons through the evolution.

IV. Physics of Compact Objects

In a collaboration with professor Vadim Urpin (IOFFE Institute, Saint Petersburg, now on sabbatical at the University of Valencia) The different criteria of convective instability have been exhaustively analyzed [4] in the scenario of new-born neutron stars.

In his Ph.D. Thesis, developed in Valencia under the supervision of J.A. Miralles, J.A. Pons built up a general relativistic stellar evolutionary code. Particular attention was payed on the neutrino transport in the interior of a proto-neutron star. With this code was possible to carry out detailed calculations of the cooling of a proto-neutron star and their neutrino spectra, for different equations of state ([13], [16] and [17]).

(C) Visits and Collaboration

- Eric Gourgoulhon (Meudon). Visited the Valencia group during 30 October – 4 November, 2000

- José A. Font-Roda (Garching). Visited the Valencia group during 4 – 11 November, 2000
- Ian Hawke (Cambridge) Visited the Valencia group during 12 – 14 March, 2001
- Jerome Novak (Meudon). Visited the Valencia group during 29 April – 6 May, 2001
- José A. Font-Roda (Garching). Visited the Valencia group during 6 – 19 May, 2001
- Joachim Frieben (AEI-Golm). Visited the Valencia group during 9 – 23 May, 2001
- J.Mª. Martín-García (Southampton). Visited the Valencia group during 23 – 28 September, 2001
- Pedro Montero (SISSA) Visited the Valencia group during 25 September – 5 October, 2001
- J. A. Pons (Rome) Visited the Valencia group during 1-28 September, 2001

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9 SISSA, TRIESTE

PERSONNEL AND GENERAL NEWS

The SISSA group participating in the Network project currently consists of two faculty members (John Miller and Luciano Rezzolla), one post-doc (Shin Yoshida) and three Ph.D. students (Olindo Zanotti, Luca Baiotti and Pedro Montero). Pedro is our research student funded from the Network and he started in October 2000.

Over the summer, Luciano was in Golm for a month, getting on with work without being bugged by the rest of our group! Shin, Pedro, Luca and John were in South Africa for almost a month, first in Cape Town, where we met up with some old friends and saw something of the surrounding countryside, then in Durban for GR16, then Krugersdorp for the Numerical Relativity workshop, then ten days of vacation, touring in the northern Transvaal and the Kruger Park. We did some very good hill-walking as well as seeing the Big 5 at home in their natural habitat (some great photos of Shin looking like a Samurai on the trail of the lions!).

For the latter part of the summer, John was in Oxford and had a visit from Nils and Ian Jones for a meeting together with Peter Jones (the person responsible for starting off the hyperon "death of the r-modes" drama). Peter (a colleague of John's at Oxford) is a nuclear physicist who is just now going into retirement and has a reputation as a somewhat reclusive guru, so it was an achievement to fix up this meeting! Indeed, it was something that John was looking forward to with some trepidation, knowing both Nils and Peter beforehand and seeing a strong possibility that this could end up as an unproductive stand-off (sorry Nils – you know what I mean!). However, in the end it went extremely well and gave some things to think about and work on further.

Back at SISSA, things are picking up again after the summer. Olindo (who was in Italy over the summer) is now going into his final year but still has calculations to do (on accretion flows) before turning attention to the thesis. He is now concentrating on a 2D code kindly provided by Toni and together with Luciano is setting up initial tests of thick tori around a Schwarzschild black hole. Pedro and Luca have finished their first-year exams and, after spending some time getting familiar with Cactus (including a visit to AEI in May), are now ready to go full-time on research. Pedro has been off in Spain for a couple of weeks, attending the Spanish Relativity Meeting and visiting the Valencia group. (We hope he will be collaborating with them on his project to investigate tori around black holes, formed after a binary neutron star coalescence.) Luca is getting his hands dirty with Cactus4 and learning how to avoid the thorns! A new post-doc is about to join us – Arun Thampan from IUCAA in Pune. He has worked on various topics in relativistic astrophysics and we are looking forward to collaborating with him, in particular on problems concerning accretion onto compact objects and properties of neutron stars (magnetic fields, r-modes, etc.)

The following is our scientific report, broken down into subsections. When possible we have highlighted the connections with the other nodes of the network

SCIENTIFIC REPORT

r-mode Oscillations and Instability

We have further investigated the impact of secular effects on the generation of large toroidal magnetic fields during the activity of the r-mode instability. The results obtained show that the magnetic fields produced could significantly reduce the amount of gravitational waves

(GWs) emitted [1, 2]. In connection with this work, we have considered the evolution of the magnetic field [3, 4] for a slowly rotating relativistic star [5]. This work aims at clarifying previous contrasting results on the subject and at providing a better understanding of how the electromagnetic information from relativistic stars together with GW data could be used to determine physical parameters of the star such as its mass and radius.

A related investigation has been carried out in order to assess the impact of differential rotation for the onset and development of the r-mode instability. We have solved the eigenvalue problem for Rossby-Haurwitz waves (the analogues of r waves on a differentially rotating thin-shell). The results obtained indicate that the eigenvalue problem is never singular and that, at least for the case of a thin-shell, r waves can be found for arbitrary large values of differential rotation [6]. This work clarifies the puzzling results of 2D calculations. As a further development of this, we have extended the results obtained in Newtonian gravity to the slow-rotation approximation in General Relativity [7].

We have also been considering further the effect on the r modes of the hyperon viscosity mechanism [8]. There are key questions about the density threshold above which hyperons appear and the cooling rate of young neutron stars both of which are potentially subject to constraints from observations.

`Work in this direction is in collaboration with Southampton and Thessaloniki`

Another outstanding issue with regard to r modes concerns how they would saturate in the non-linear regime. One suggestion is that, beyond a certain critical amplitude, they would give rise to shocks in the outer parts of the neutron star which would then prevent further growth of the mode. We have been investigating this possibility and have found that it is quite plausible that this could give rise to a maximum for the amplitude parameter α of order one or, perhaps, considerably less as long as some other saturation mechanism does not enter first [9]. This study has highlighted the need to be wary of using Newtonian (or partly-Newtonian) methods to calculate this and the need for having sufficient spatial resolution in numerical calculations in order to get reliable results.

`Work in this direction is in collaboration with Thessaloniki`

Neutron Star Equations of State

It is clear that there is an important link between the objectives of the Network and studies of neutron star equations of state. Predictions coming from the equations of state are important for making predictions about GW production and, in turn, when GWs have been seen, there is the prospect of giving crucial new input into studies of high density matter using data from astronomical objects. The link between laboratory data for heavy nuclei and conditions in neutron stars is in an intriguing regime (the conditions are in some senses quite similar but in others very different). We have been investigating an approach for densities around nuclear matter density using the separable monopole interaction which has previously had great success in accounting for laboratory data but had not previously been applied for neutron stars [10].

Advanced Methods in Relativistic Hydrodynamics

In the context of the construction of improved methods for relativistic hydrodynamics, we have investigated a new approach to the solution of the exact Riemann problem in 1D which optimises both computational costs and simplicity of implementation [11]. This new method can also be extended to the case of nonzero tangential velocities and can therefore be implemented also in multi-dimensional relativistic hydrodynamics codes. Furthermore,

the use of this novel approach had made it possible to point out the occurrence of interesting new relativistic effects [12].
`Work in this direction is in collaboration with Rome and Valencia`

Long-term Dynamics of Isolated Relativistic Stars

Using a new 3D general-relativistic hydrodynamics code built by the AEI/WashU collaboration, we have studied the long-term dynamics of relativistic stars, focusing on the pulsations of stable and unstable, rotating and non-rotating relativistic stars. We have considered both the nonlinear radial oscillations of spherical stars and linear perturbations of rotating stars. The frequencies obtained from these fully numerical calculations are in excellent agreement with those obtained from perturbation theory. A major result in this sense has been the calculation of the first mode-frequencies for rapidly rotating stars in full General Relativity. This has been a long-standing problem; such frequencies have not, so far, been obtained by perturbative methods [13]).
`Work in this direction is in collaboration with Golm, Paris, Thessaloniki and Valencia`

Accretion onto Black Holes

Our network research student, Pedro Montero, has as his Ph.D. project the investigation of configurations consisting of a stellar-mass black hole encircled by a torus of high-density matter. These possibly occur as important transient configurations after the coalescence of neutron-star binaries. Study of them is related to more standard studies of accretion flows around black holes which have been the subject of a main line of research at SISSA for a number of years [14]. Those studies are ongoing and it is hoped that some of the expertise gained there can be profitably transferred to the problem of the high-density torus even if the physical conditions in a standard accretion flow are rather different from those in the torus. Also, Rezzolla and Zanotti are hoping to benefit from related work using on a 2D HRSC code written by Toni Font to simulate relativistic accretion of thick tori around Schwarzschild black holes.
`Work in this direction is in collaboration with Valencia`

The research on standard disc accretion by Miller and Szuszkiewicz has been investigating various forms of non-stationary behaviour in accretion flows onto black holes including, in particular, possible limit-cycle behaviour and its relation to the periodic emission of plasma blobs which may be related to the origin of jets. The code is currently being re-written to make it more robust and flexible, allowing it to be used to study a wider range of physical situations. A particularly important extension concerns the capacity to handle a two-temperature plasma (with the ions and electrons having different temperatures). It is widely expected that when this is included, true ADAF-type behaviour will be seen.

Gravitational Wave Emission from Cataclysmic Variables

GW emission is considered to be the driving force for the evolution of short-period cataclysmic variable binary stars (CVs), making observations of them a potential test for the validity of General Relativity. When modelling the binary system, simplified Roche model approximations have previously been used with the GW emission being estimated with the quadrupole formula for point-masses. We have calculated the GW emission on the basis of self-consistent solutions of Roche lobe filling binary configurations taking into account all of the corrections due to the finite sizes of the sources. The results obtained indicate that enhanced GW emission cannot be used to explain the minimum period puzzle for CVs [15].

Critical Collapse in an Expanding Background

We have studied the dynamics of critical collapse in an expanding Einstein-de Sitter spacetime in order to find out how the presence of a cosmological constant modifies the scaling relation. For doing this, we have used a 1D numerical general relativistic code using null foliation and Lagrangian hydrodynamics. The results obtained indicate that inclusion of the cosmological constant does cause a change in the exponent of the scaling relation, with the direction of the change depending on the sign of the constant. This can be easily interpreted if one thinks of the introduction of the cosmological constant being effectively equivalent to changing the equation of state so that the collapse is made either easier or more difficult [16]. We plan to extend the experties gained in this calculation to the study of perturbations in gravitational collapse.
`Work in this direction is in collaboration with Rome`

Scalar Stochastic Background of Gravitational Waves

We have computed the sensitivity of pairs of laser interferometers and resonant mass gravitational wave detectors to a scalar stochastic background of gravitational waves. Our computations have been carried out both for minimal and non minimal coupling of the scalar fields [17]

In what follows we list the papers produced by the group since August 2000 with the papers in proceedings completing the list.

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10 PALMA DE MALLORCA

The Relativity and Gravitation group at the Universitat de les Illes Balears (Palma de Mallorca) has been in operation since mid 1980s. Current members of the group are: Dr. Carles Bona (Prof., Local Coordinator), Dr. Llus Mas (Prof.), Dr. Joan Mass (Assoc. Prof.), Dr. Joan Stela (Ass. Prof.) and Dr. Jaume Carot (Assoc. Prof.). Since the time the EUnetwork proposal was submitted, some changes in the composition of the group have taken place; thus, in particular, two new doctoral students have joined the group: Magdalena Collinge and Carlos Palenzuela (Ph.D. program funded by the Local Government of the Balearic islands). Also, and after a previous process of selection amongst a number of candidates, we have interviewed a three prospect Post-doctoral fellows (Dr. M. Tiglio, Dr. T. Wolf and Dr. P. Miocchi); but none of them could join our group due to various personal reasons.

Prof. C. Bona and Mr. C. Palenzuela attended the first Network meeting in Potsdam (Dec. 7-9, 2000), and Prof. C. Bona attended the second Network meeting in Thessaloniki (June 6-10, 2001). Also, Prof. C. Bona and Mr. C. Palenzuela participated in the ERE-2001 (Spanish Relativity Meeting) in Madrid (September 17-22, 2001) where preliminary results on the topics discussed below were presented [1].

Following the Work Plan of the network, our group, in collaboration with the AEI, is involved in the tasks (a.1) and (a.2), i.e.: Continued development of Cactus and Vacuum BH evolutions respectively.

Continued development of Cactus

Our work in this area is mainly centered in the following topics:

1. **Refinement of Evolution Methods:** Our starting point has been the Bona-Mass FOFCH (First Order Flux Conservative Hyperbolic) system of equations[2], where the evolution has been split using 'Strang Splitting' into one step for the evolution of the fluxes (transport) plus two steps for that corresponding to the sources. In order to avoid instabilities in areas of large gradients during transport (e.g.: in the case of BH those resulting from choosing a singularity-avoiding slicing), we are currently implementing advanced methods in CFD (Computational Fluid Dynamics) in the 3D case; namely: Flux Limiter methods[3] where the hyperbolicity of the Bona-Mass system is explicitly taken into account.

   In order to do this, we previously had to develop a new numerical algorithm in order to implement those methods. This new algorithm is essentially based on the computation of the fluxes in the interphases and proceed then by dealing with one direction at a time, neglecting the fluxes in the non-relevant directions and evaluating the eigen-fluxes and limiting each way in that direction. We tested the algorithm, with complete success, first in the case of the 3D wave-equation (since it displays certain similarities with one specific problem that also appears in the case of Einstein's field equations (EFEs)). When applied to EFEs, new problems appeared -as expected- but they have been overcome almost completely at the time of writing this.

   Next step will be to implement both the Bona-Mass evolution system and the above algorithm based on flux limiter methods, as Cactus thorns.

As a side development in this area, the case of a 2D code with a view towards dealing with axially symmetric systems was investigated and coordinate singularities appeared when approaching the axis of symmetry (in quite a different way than those occurring in the case 1D corresponding to spherical symmetry when the center is approached); this gave rise to a detailed study of the geometric properties of regions close to the axis, with an emphasis on its characterization via different admissible sets of coordinates; deriving normal shift-free forms for the metric and finding the leading power dependence on the radial coordinate of the metric potentials [4], thus allowing for an explicit 'a priori' cancellation in both members of the equations of the terms responsible for the numerical instabilities.

Independently, but also in the axisymmetric context, the evolution of matter in axially symmetric black holes has also been looked into [5].

2. **Formulation of equations:** Starting again from the Bona-Mass FOFCH, we are currently re-writing the equations by re-writing in turn some of the source terms (in particular those corresponding to V, which are related to the momentum constrain, and those corresponding to the extrinsic curvature K), since we have shown that some of the terms appearing in those sources are responsible for the increase at every point of the numerical instabilities in the constrains. By re-writing appropriately those terms we make them vanish over the boundaries, thus achieving a greater stability in the evolution of the sources.

Vacuum BH evolution

Once the developments on the new algorithm described above (based on flux limiter methods) are completed, we shall apply it to evolve one BH using appropriate initial conditions. Once this is done, we aim at evolving a binary system using the coordinate freedom the system has in order to set up a particular co-moving system.

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