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Department	Department of Physics
Group	Institute for Theoretical Physics

Project name	**General Relativistic Simulations of Black-Hole-Torus Systems with Microphysics**
Working groups	Astrophysics, Gravitational Physics

1 Report

I visited the Department of Astronomy and Astrophysics (DAA) at the University of Valencia from January 20 till January 30, 2015.

Together with Prof. José A. Font and Vassilios Mewes, we have developed the necessary infrastructure to include the effects of neutrinos in our recent simulations of black-hole-torus systems [4]. In this work, we have studied non-axisymmetric instabilities in self-gravitating disks around black-holes (BHs) using three-dimensional hydrodynamical simulations in full general relativity. In particular, we concentrated on configurations build with the assumption of hydrostatic equilibrium, axisymmetry and constant angular momentum. Despite the vast literature on this topic, the astrophysical significance of such type of models is uncertain as they do not seem to be favoured as the end-product of self-consistent numerical relativity simulations of binary neutron star (BNS) mergers.

As detailed in the proposal, we have proceeded along two lines of work:

(a) *Implementation of neutrino radiative losses*. The neutrino radiation is treated approximatively by means of a so-called *leakage* scheme [1], in which suitable source terms are added to the basic equations of relativistic hydrodynamics to account for the radiative losses. Furthermore, we have extended the leakage scheme to include the effects of neutrino heating. In order to account for the fact that part of the neutrinos are reabsorbed in the thick and hot torus material we have included two additional evolution equations for the neutrino number density and for the mean energy with appropriate source terms proportional to the absorption rates. These equations are solved on the spherical grid used to compute the optical depth and assumes that most of the neutrinos will escape radially from the system.

We have successfully tested this new scheme in a simulation of BNS merger coupled with a nuclear equation of state (EOS) with density, temperature and electron fraction dependence. The initial data for this simulation describes an equal-mass binary system with two NS of baryonic mass $M_b = 1.4 M_\odot$ in an eccentric orbit and an initial separation of 50 km. The nuclear EOS employed is the Lattimer-Swesty with incompressibility modulus $K = 220$. For this simulation we have included only the effect of neutrino cooling given the extremely short life of the metastable NS formed after the merger. On the left panel of Fig.1, we show the evolution of the maximum rest-mass density where it clearly visible the exponential increase right before a BH is formed at the end of the simulation. On the right panel, the luminosities of electron neutrinos, electron antineutrinos and heavy neutrinos (τ and μ neutrinos and antineutrinos) show a strong correlation with the evolution of the central density due to the temperature increase induced by compression in the metastable NS. The end

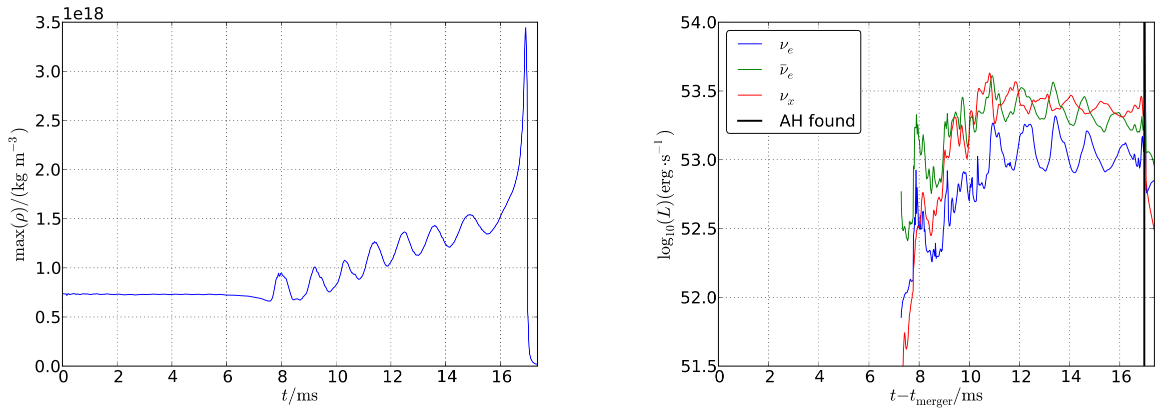

Figure 1: *Left:* Evolution of the maximum rest-mass density for a BNS system of $M_b = 1.4M_{\odot}$ (see the text for the details). *Right:* Luminosities of electron neutrinos ν_e, electron antineutrinos $\bar{\nu}_e$ and heavy neutrinos ν_x (τ and μ neutrinos and antineutrinos).

state of the simulation is a rotating BH surrounded by a thick hot torus of $0.01M_{\odot}$ with an angular velocity distribution that approaches the Keplerian limit in the outer edges. The long term effects of neutrino cooling on this system might influence the accretion rate onto the BH leading to a different growth-rate of both axisymmetric and non-axisymmetric unstable modes.

(b) *Realistic models of black-hole-tori from binary neutron star mergers*. In the second part of the project we have addressed the problem of finding a suitable set of initial data for the BH-torus simulations. The outcome of a BNS merger, as the one described in the previous section (see Fig. 1), will provide the starting point for our simulations. Recent numerical relativity simulations of [3, 2] have shown that, indeed, those systems do not manifest signs of any dynamical instability on short dynamical timescales but, however, on longer timescales, non-axisymmetric instabilities may set in.

The main numerical challenge in this approach consists in remapping the final stage of the BNS simulation onto a mesh refinement structure better suited to capture the BH-torus system. Given our previous experience in evolving similar systems, we found that high resolution is required in the inner part of the disk to resolve accurately the accretion onto the BH. At the same time the finest refinement level in the BNS simulation does not cover the all extent of the disk and for this reason it is necessary to interpolate the metric and fluid fields onto a largest grid with higher resolutions (see left panel Fig. 2). This procedure introduces numerical errors that might spoil the results of our simulations and for this reason we will quantify this effect in the second phase of the project.

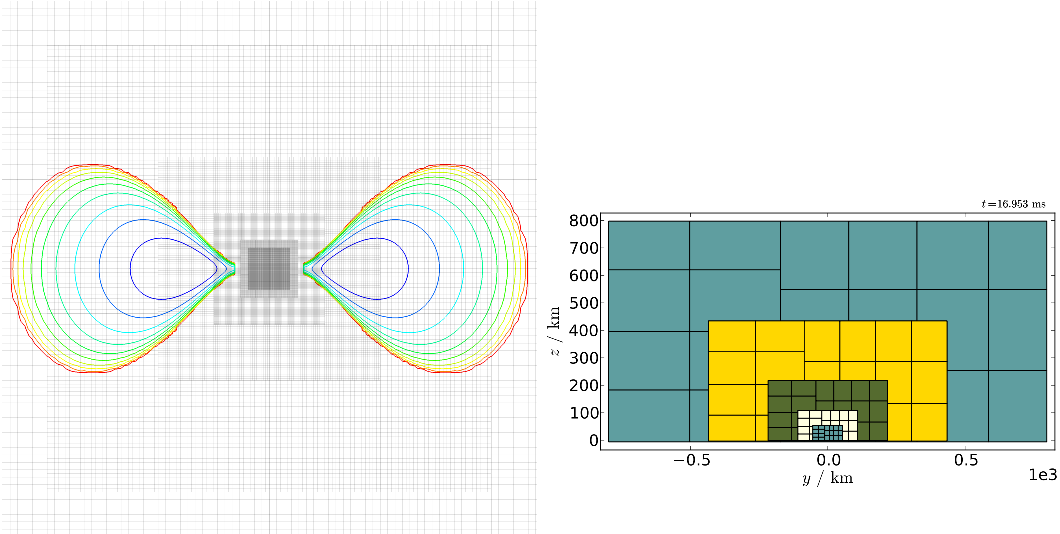

Figure 2: *Left:* Contour plot in the xz-plane of the initial density profile for one of the disk models in [4]. The grid structure shows the 6 innermost mesh refinement levels (out of 13) employed in the simulation. The box is 68 km of length across. *Right:* Mesh refinement structure on the xz-plane at the end of BNS simulation describe in the text. The total number of mesh refinements is 7.

2 Remaining work and dissemination of the results

I plan to continue collaborating with Prof. José A. Font and V. Mewes and to finish the projects started during this visit. We want to perform several BNS simulations with different EOSs and with a total mass of the binary above the threshold necessary to collapse to BH. The final stage of these simulations will provide several disk models to use as initial data. The next step involves the long term evolution of these models for several tens of orbits including the effect of neutrino radiation.

I do expect publications from both projects in the coming months, in which the STSM of the COST action will also be acknowledged. Furthermore this work will be part of V. Mewes' PhD thesis that will be completed by the end of 2015.

During the visit, I also had the opportunity to work closely with Dr. P. Cerda-Duran, Dr. M. Obergaulinger and Dr. B. Peres on an ongoing project of code comparison amongst the different formulations of the neutrino leakage scheme.

References

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