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TEST OF AN MHD CODE FOR COSMOLOGICAL APPLICATIONS

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RESUMEN

Hemos compilado una colección de pruebas MHD que contienen varios problemas de choques en tubos y diferentes problemas planos (como el vórtice Orzang-Tang, ondas explosivas y un rotor rápido). Para probar la implementación MHD (Dolag & Stasyszyn, in prep.) efectuada dentro del código SPH con aplicación cosmológica Gadget (Springel 2005), hemos implementado condiciones iniciales en tres dimensiones totalmente consitentes con las condiciones iniciales usadas en aplicaciones cosmológicas. Los resultados son comparados con las soluciones idealizadas en 1D/2D obtenidas usando Athena 3.0 (Gardiner & Stone 2006), mostrando que la implementación tiene un desempeño muy bueno. También comparamos diferentes esquemas de regularizacion de SPH MHD sugeridos en la literatura, e intentamos calibrar dichos esquemas infiriendo los valores óptimos para los diferentes parámetros numéricos involucrados. También probamos una implementación de un esquema de limpieza Hyperbólico/parabólico de la divergencia, encontrando acuerdo con los resultados reportados en la literatura (Price & Monaghan 2005).

ABSTRACT

We build up a comprehensive MHD test suit containing various shock tube tests and different planar MHD test problems (like the Orzang-Tang Vortex, Blast Waves and a Rotor test). To test the MHD implementation (Dolag & Stasyszyn, in prep.) within the cosmological SPH code Gadget (Springel 2005), we performed fully consistently three dimensional setups to test the code under the same conditions as used the cosmological applications. The results were compared with the idealized solutions obtained in 1D/2D using Athena 3.0 (Gardiner & Stone 2006), showing us that the SPH MHD implementation performs very well. We also compare different regularization schemes of SPH MHD suggested in the literature, and calibrate theses schemes inferring optimal values for the numerical parameters involved. The Implementation of a Hyperbolic/Parabolic divergence cleaning scheme as suggested by Dedner (Dedner et al. 2002) have been also tested, finding good agreement with the results reported in the literature (Price & Monaghan 2005).

Key Words: cosmology: miscellaneous — methods: numerical — MHD

1. INTRODUCTION

Eulerian codes were the first to successfully deal with MHD simulation problems. However the adaptive resolution and easy nature of the calculation of self gravity made Smoothed Particle Hydrodynamic (SPH) codes a natural alternative for solving Astrophysical problems, especially for structure formation simulations where a large dynamical range is needed. Just in the past years MHD Lagrangian codes have become accurate enough to compete with Eulerian codes and face Astrophysical problems with success. Here we present a comprehensive MHD test suit containing various shock tube tests and different planar MHD test problems (like the Orzang-Tang Vortex, Blast Waves and Rotor test) applied to the SPH MHD implementation in Gadget. The aim is to show the acuracy of the present code, obtaining good agreemnt to different methods. The final technical details can be found in (Dolag & Stasyszyn, in prep.). First we show the performance with shock tube tests in the § 2, the two dimensional tests in § 3, the results for the implementation of the divergence cleaning schemes is in § 4 and finally our conclusions.

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2. SHOCK TUBE TESTS

Using a set of 11 shock tube setups as suggested in (Ryu & Jones 1995), we checked the performance of the numerical implementations under different conditions, the results are presented in Figure 1.

2.1. **Brio-Wu** *Test*

One of the 11 tests we perform is the called Brio-Wu (Brio & Wu 1988). We choose to show this test in detail with the different regularization schemes implemented, because is the most used in literature to check MHD codes. Figure 2 show the results for the test in the case of the standard implementation of MHD in Gadget, which uses a symmetric formulation based on the Maxwell Tensor (Monaghan 1997)

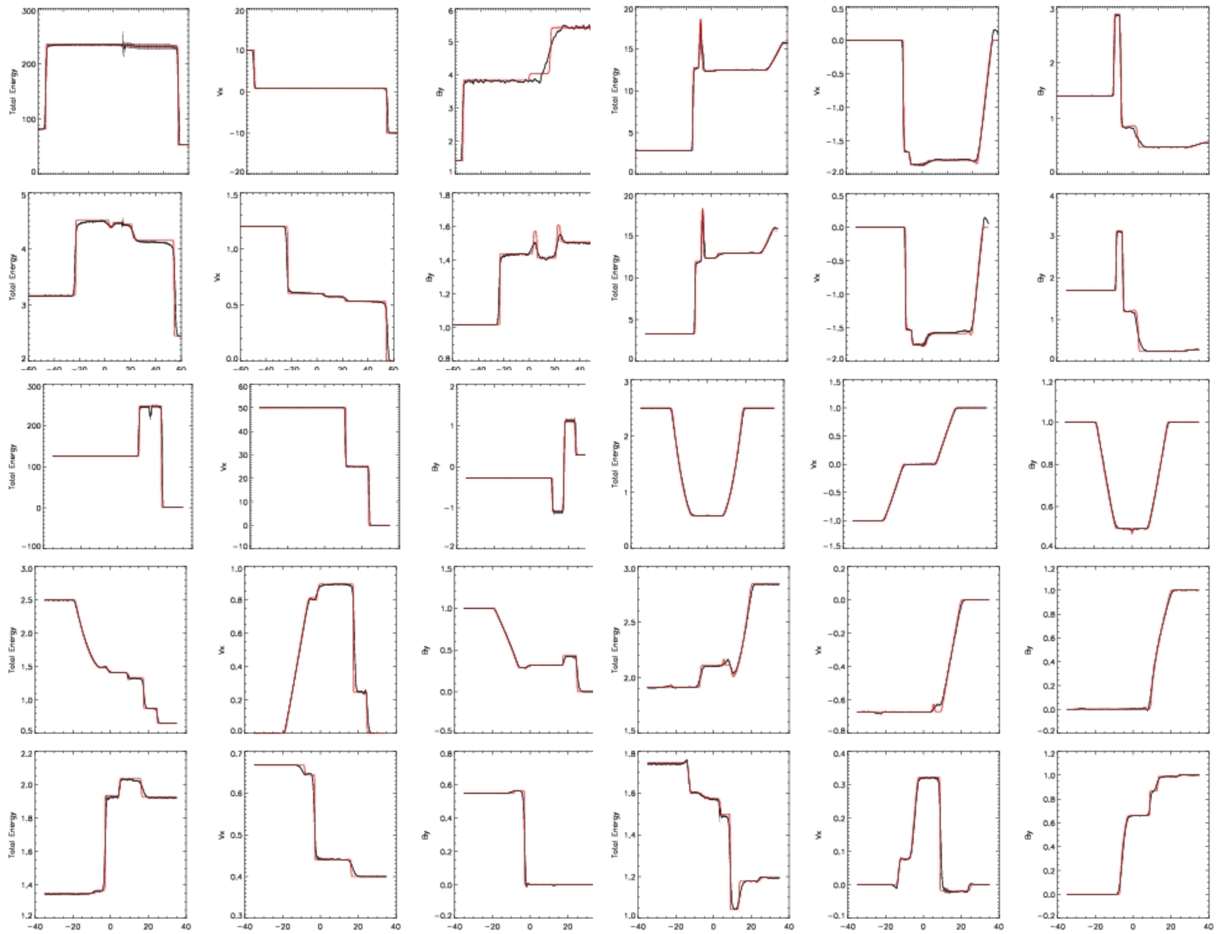

Fig. 1. Full set of Shock tube tests runed.

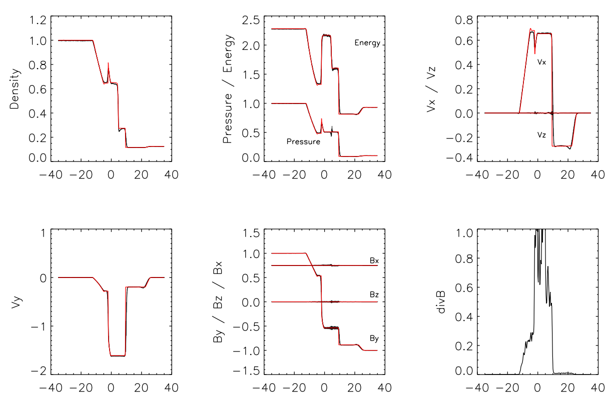

Fig. 2. Normal run of the **Brio-Wu** Test.

supplemented with a $\nabla \cdot \vec{B}$ correction term (Børve et al. 2001) for the calculation of the force. Additionally the formulation of the artificial viscosity is based on the magnetic signal velocity (Price & Monaghan 2005). The individual sub-panels shows the density, total energy and pressure, velocity in x and z direction, velocity in y direction, $\vec{B}$ field in each dimension, and divergence of $\vec{B}$, along the x axis. The idealized Athena run is shown in Red and in Black the Gadget run. In the Figure 3 we show the results for a regularization of the magnetic field by smoothing the field (Børve et al. 2001). In the Figure 4 we show the results obtained using a regularization scheme based on artificial dissipation (Price & Monaghan 2004a). We see that the result for the standard scheme produces reasonably good solution. In the regularizations cases, there is a considerable drop in the values of the divB and the noise, but on the other hand sharp features (as shock capturing capabilities) may be suppressed.

2.2. *Full set of shock tube tests*

We perform the full set of tests varying the parameters for the two different regularization schemes, to be able to calibrate them. The panels on the Figure 1 show the total energy, velocity in the x direc-

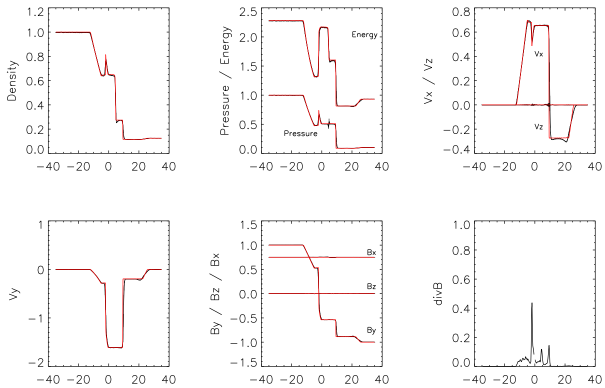

Fig. 3. The **Brio-Wu** Test smoothing the $\vec{B}$ field each 30 timesteps.

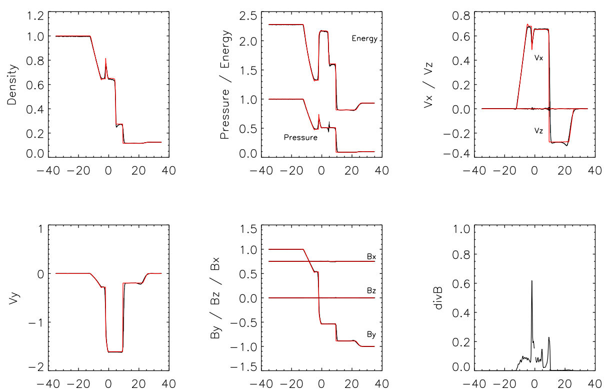

Fig. 4. The **Brio-Wu** Test using artificial magnetic dissipation.

tion and the $\vec{B}$ field in the y direction for all the rest of these tests. For this plots we used the regularization scheme where the magnetic field is smoothed periodically using the same settings as used in previous cosmological simulations (Dolag et al. 2005). The Athena run is shown in red and the Gadget run in black. Each of these tests produce different types of waves, and these features react differently to the numerical parameters for the regularizations schemes.

2.3. *The Best Numerical Parameters*

We defined two estimators for measuring the goodness of the individual simulations. First we calculated the mean $|div(\vec{B})|/|\vec{B}|$ at the final time as indicator of numerical errors. As an estimator of how good we capture shocks and contact discontinuities, we calculate the mean error weighted difference between the prediction for the magnetic field, e.g. the results obtained from Athena, and the numerical results obtained with Gadget (error estimator). The

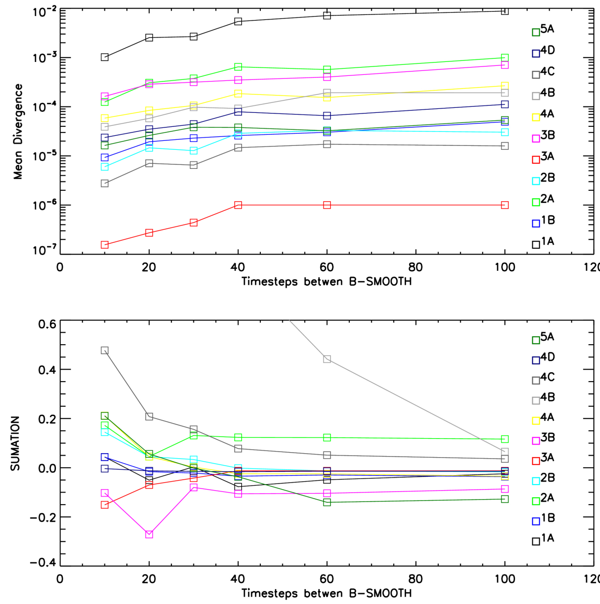

Fig. 5. Comparison between the different tests and smoothing frequencies. In both pannels lower values are better.

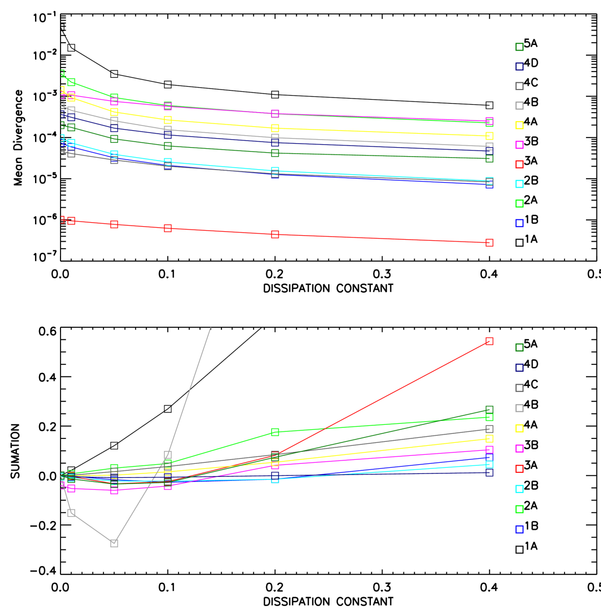

Fig. 6. Comparison between the different tests and artificial dissipation constant. In both pannels lower values are better.

two panels on the Figure 5 show these estimators as function of the time interval between the regularizations by smoothing the $\vec{B}$ field.

In the Figure 6 we show the two estimators as function of the strength of the artificial magnetic dis-

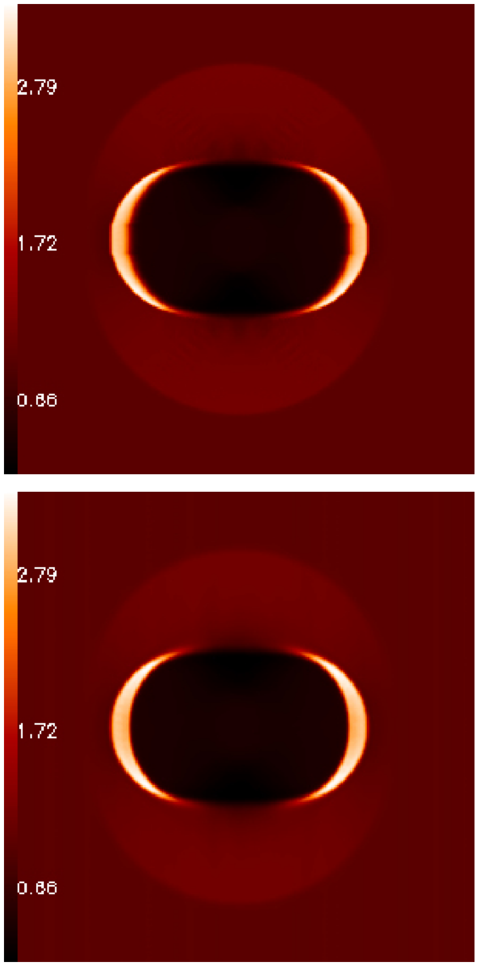

Fig. 7. Strong Blast problem, density distribution. At the top the Athena solution and at the bottom the Gadget solution at time 0.02.

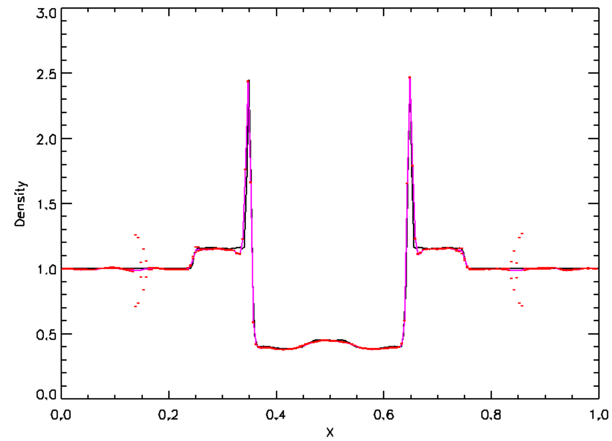

Fig. 8. Strong Blast density cut at time 0.02 and $y = 0.5$.

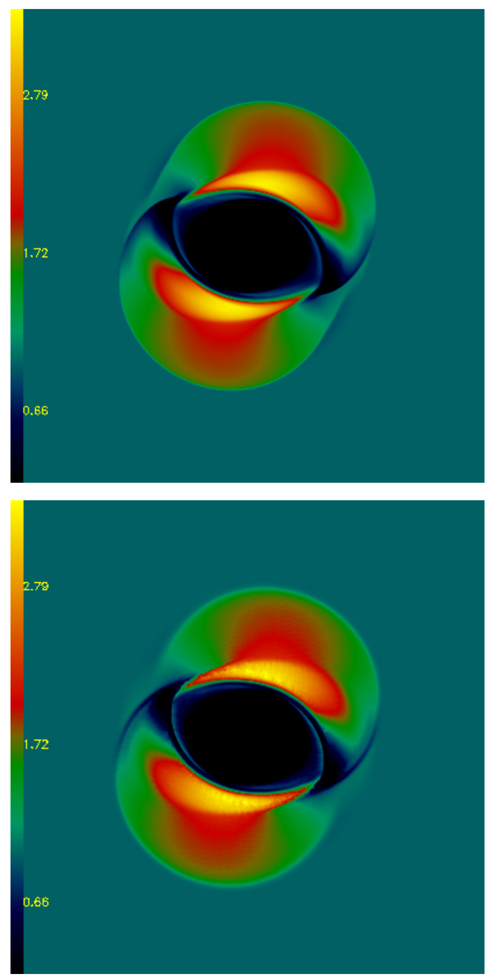

Fig. 9. Rotor test problem, Magnetic pressure distribution. At the top the Athena solution and at bottom the Gadget solution at time 0.1.

sipation in the second regularization scheme. One can see that the $div(\vec{B})$ estimator gets better the stronger the regularization is applied. However the error indicator shows that too strong regularization leads to smearing of features.

3. PLANAR TESTS

The results obtained with the standard implementation for the Orzang-Tang Vortex (Orszag & Tang 1998; Londrillo & Del Zanna 2000), Rotor (Londrillo & Del Zanna 2000; Balsara et al. 1999) and Strong Blast (Londrillo & Del Zanna 2000; Balsara et al. 1999).

All theses tests are performed in full 3D with Gadget and in 2D with Athena. The Figure 7 show the density through a slice of the strong blast test and an one dimensional cut at $y = 0.5$ comparing the two solutions is shown in Figure 8. In Black the

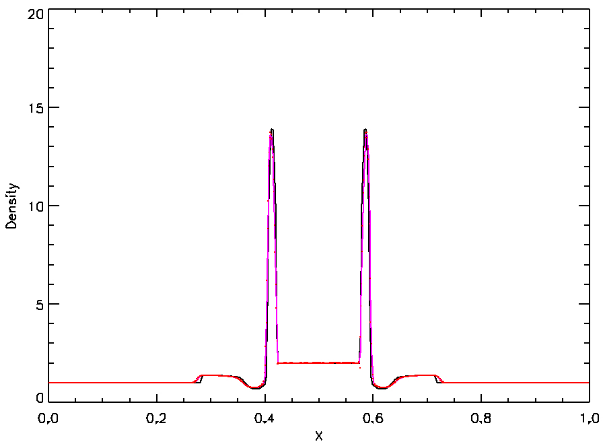

Fig. 10. Rotor test density cut at time 0.1 and $y = 0.5$.

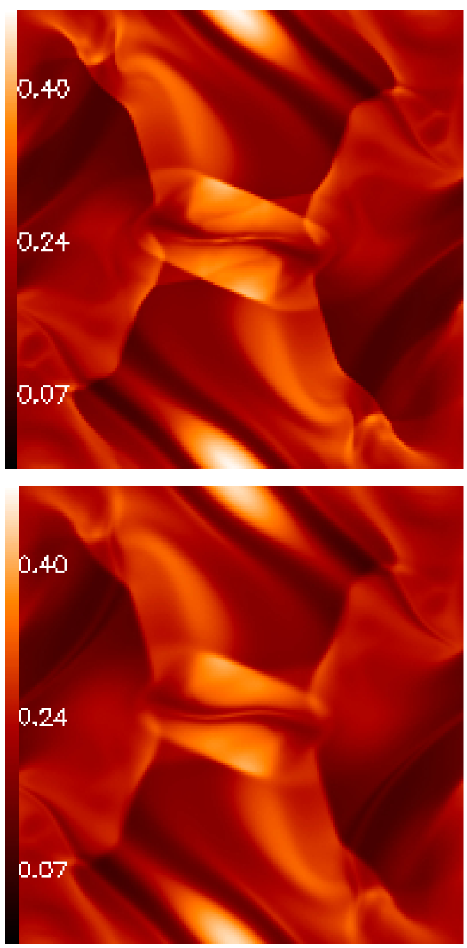

Fig. 11. Orzang-Tang problem, density distribution. At the top the Athena solution and at bottom the Gadget solution at time 0.5.

Athena Solution, in Magenta our numerical solution and in Red the error bars. In the Figure 9 we show a

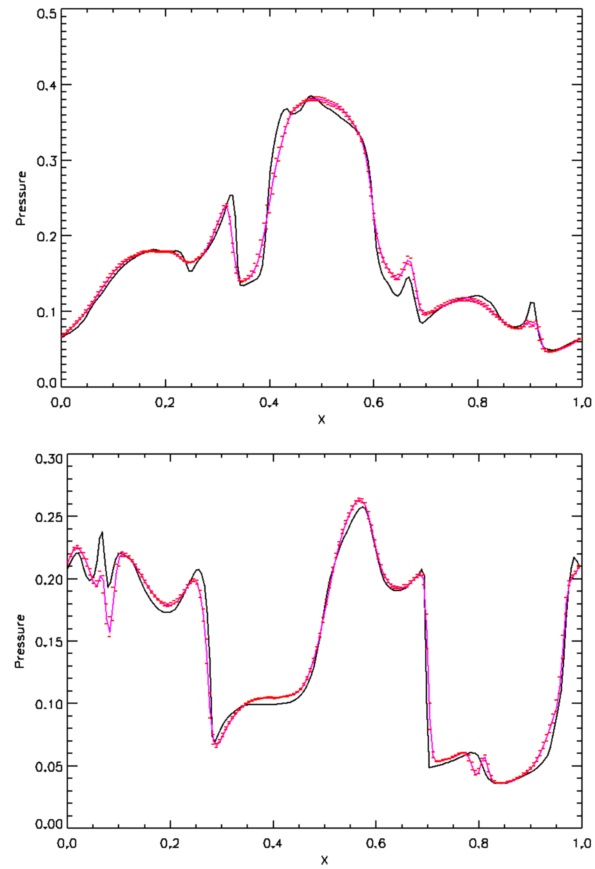

Fig. 12. Vortex pressure cut at time 0.5 and $y = 0.4277$ (first) and $y = 0.3125$ (second).

slice of the $\vec{B}^2$ for the Rotor and an one dimensional cut of the density at $y = 0.5$ in s shown in Figure 10. The Figure 11 shows the density of the evolution of the Vortex at time 0.5. The Figure 12 shows in two panels two one dimensional cuts at $y = 0.4277$ and $y = 0.3125$ (as often used in literature). The standard Gadget-MHD implementation shows very good results. A complete set of tests with the different regularization schemes is in progress.

4. DIVERGENCE CLEANING

As proposed by (Dedner et al. 2002; Price & Monaghan 2005), we implemented a Hyperbolic/Parabolic Divergence cleaning scheme in Gadget (Stasyszyn & Dolag, in prep.). In this method an additional scalar field is evolved which diffuses and dissolves the $div(\vec{B})$ sources. In the Figure 13 results are shown for a magnetic field advection test (Dedner et al. 2002; Price & Monaghan 2005). The magnetic field setup is made to produce a non zero $div(\vec{B})$ at initial time.

The two time sequences show the evolution of the system with and without the $div(\vec{B})$ cleaning

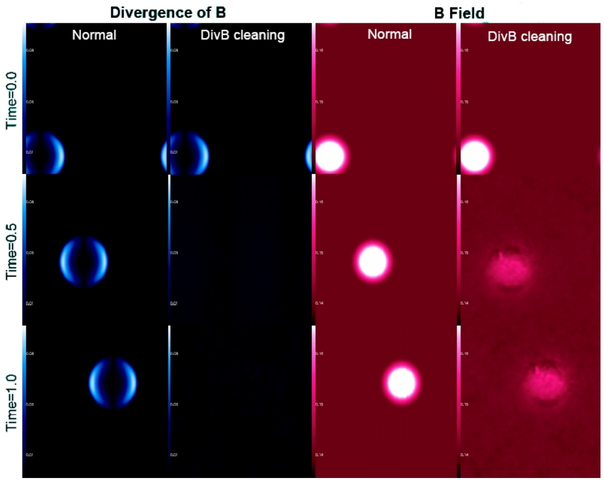

Fig. 13. Advection test. Evolution of the $\vec{B}$ peack field and $div(\vec{B})$.

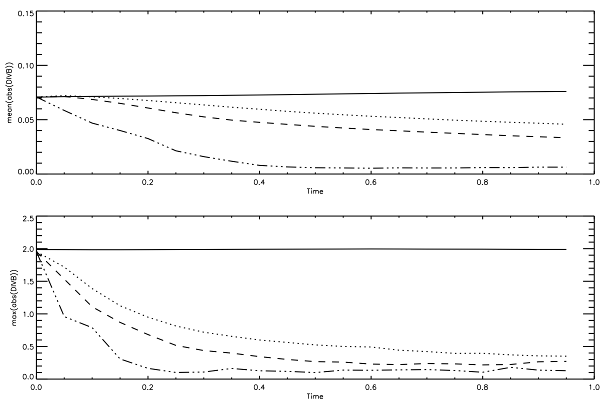

Fig. 14. Evolution of the divergence of the $\vec{B}$ field trought time and with different input parameters.

scheme. This nicely demonstrate that our standard implementation does not suffer from any numerical artifacts even in the presence of significant $div(\vec{B})$. Depending on the chosen strength of the Hyperbolic/Parabolic part of the $div(\vec{B})$ cleaning scheme the initially present $div(\vec{B})$ is reduced and diffuses away as shown in the Figure 14, which shows the evolution of the mean and the maximum of $div(\vec{B})$ for different numerical parameters in this scheme.

The Figure 15 shows one of the shock tube tests using this scheme, showing significant reduction in the $div(\vec{B})$ values, one can compare the shape of the shock and the values of $div(\vec{B})$ in the normal run showed in Figure 2.

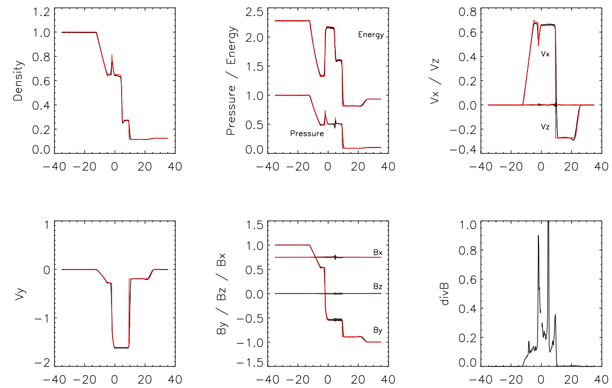

Fig. 15. **Brio-Wu** Test using the Hyperbolic/Parabolic divergence clenaing scheme. Comparable with Figure 2.

5. CONCLUSIONS

We applied the MHD implementation within the cosmological SPH code Gadget to a large set of test problems. These tests are performed consistently in fully 3D setups to allow us to judge the performance under realistic circumstances. In general the results compare very well to the ones obtained in 1D/2D by the Eulerian MHD code Athena. A full set of tests with different regularization schemes (Price & Monaghan 2005; Børve et al. 2001) allowed us to further improve the numerical results by optimizing the parameters involved in the different schemes. The implementation of the Hyperbolic/Parabolic divB cleaning scheme (Dedner et al. 2002) leads to promising improvements in the results, but more studies have to be done.

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