NOVAs: a Numerical Observatory of Violent Accreting systems

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ABSTRACT

Here we are presenting NOVAs, a Numerical Observatory of Violent Accreting systems, which couples a GR AMR MPI (GRAMRVAC) code able to follow accretion around a Kerr Black-hole with the ray-tracing code GYOTO. Together, they allow us to test different models by running the simulation and obtaining spectral energy distributions and power-density spectrums from which we can extract the same observables as for 'real' observations, hence making it a Numerical Observatory.

1 Introduction: why a numerical observatory?

While there are a lot of observational data and theoretical models trying to explain them, it is hard to bridge the gap between observables, such as the energy spectrum for example, and an analytical or numerical model. This is especially true when looking at highly relativistic system such as the inner region of an accreting black-hole.

The idea behind NOVAs is to create consistently, from numerical GR-(M)HD simulations the same outputs as we have from observations, *i.e.* lightcurve, energy spectrum and Power-Density Spectrum, in a compatible format to be analyzed by software like `xspec`. It makes use of several existing or in development codes which are:

`GRAMRVAC` All the general relativistic (GR) fluid dynamics are done with the general relativistic version of MPI-AMRVAC[1]. In most of the simulations presented here we used a Harten, Lax and van Leer (HLL) solver linked to a Koren slope limiter[1,2].

`GYOTO` For all the HR ray-tracing computations, we use the open-source[2] GYOTO code. Photons are traced by integrating the geodesic equation using a Runge-Kutta-Fehlberg adaptive-step integrator at order 7/8 (meaning that the method is 8th order, with an error estimation at 7th order). From such maps of specific intensity, the light curve (flux as a function of time) is derived by summing all pixels weighted by the element of solid angle, which is subtended by each pixel.[3]

`SIXTE` In order to add instrumental effect we use the SIXTE[3] package for X-Ray telescope observation simulations. It allows to undertake instrument performance analyses and to produce simulated event files for mission- and analysis studies.

On top of developping the GR formalism for `GRAMRVAC` we have added to the codes, when needed, new outputs and formats so that one can smoothly go from the fluid simulation to the spectrum observed by an instrument.

2 How does NOVAs works

Fig.1. shows how the numerical observatory of `NOVAs` works when compared with 'standard' observations. This emphasized how a numerical observatory is complementary of 'standard' observation.

[1]Freely available at https://github.com/amrvac/amrvac
[2]Freely available at http://gyoto.obspm.fr
[3]Freely available at https://www.sternwarte.uni-erlangen.de/research/sixte/index.php

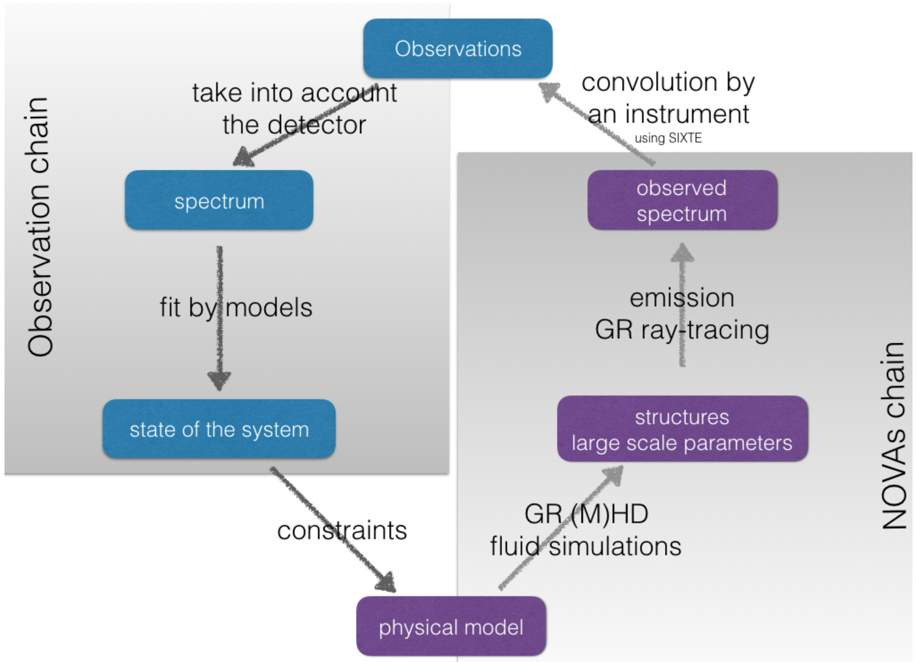

Figure 1. How the 'standard' observation chain compare with the `NOVAs` chain.

The NOVAs chain starts from a physical model, in our example below we have matter orbiting around a Kerr black hole of spin a, mass M. The first step is to use `GRAMRVAC` to evolve the system in order to obtain a self consistent disk. Here we are particularly interested in the shape of the inner edge, left Fig.2.

Once we have the overall structure of the system and the large scale parameters we use `GYOTO` to ray-trace back to the observer the emitted flux as a function of energy, middle Fig.2.

Lastly, those can in turn can be translated into an energy spectrum for the source directly or going through a non-perfect instrument using `SIXTE`, right Fig.2.

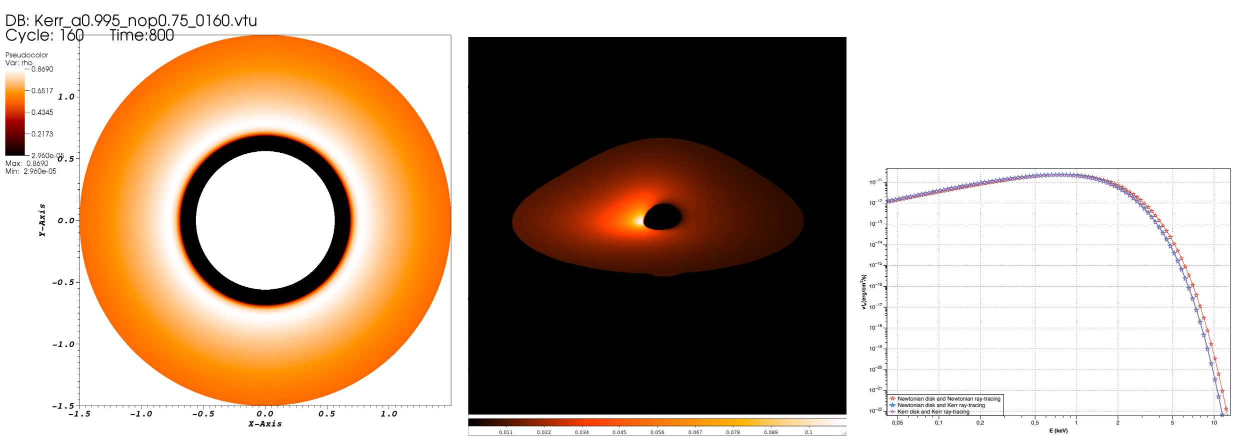

Figure 2. Left: snapshot from the GR-HD simulation leading to the creation of a disk. Middle: the emission ray-traced back to the observed for a perfect instrument. Right: energy spectrum of the same snapshot.

There are numerous application to that numerical observatory, among them we can make prediction from model, test how certain observed features can be explained, test the impact of parameters that are hard to pinpoint such as the inclination, and also test the detectability of certain feature with new instrument using `SIXTE`.

3 First Applications

Here we are presenting a few applications of our numerical observatory showing how it can used to improve our understand of observations.

3.1 Testing the efficiency of a fitting model

As the output of `NOVAs` is compatible with `xspec` we can use the standard fitting procedure on our numerical observations and assess how close the fitted parameters are to the one inputed in the simulation.

Using the case presented in Fig.2 we ran simulation of an accretion disk formed around different spin black-holes and them used the `kerrbb` model to fit the spin value from the energy spectrum. To simplify the test we inputed the exact value of inclination, mass and distance of the NOVAs observation, letting only the spin to be fitted. The resulting fitted spins are represented in Fig.3 with respect to the spin of the numerical observation.

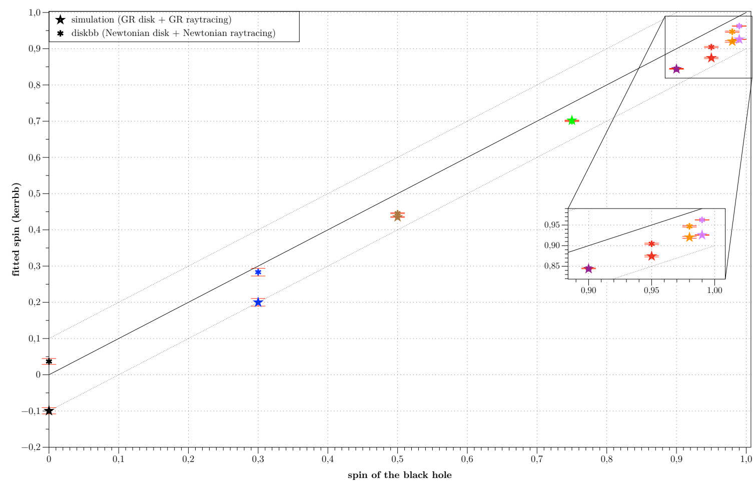

Figure 3. Comparison between the spin of the numerical observation and its fitted value.

For all the spins the fitted value is within 0.1 of the actual spin of the numerical observation and the quality of the fitted value improves as the spin increases. It is interesting to note that, for all of the case explored here, the fitted value was always lower than the actual spin of the object. This is a preliminary study and more cases need to be explored but it is showing a good efficiency of the spin fitting method if we know well the system's parameters.

3.2 Understanding the origin of some observed features

Another possible application of the `NOVAs` framework is to look for the cause of some observed features. Here we are looking at what could be the reason behind the fact that it is harder to obtain good χ^2 for the spectral fit of high-spin systems, and that for every states.

In order to explore the difference between high and low spin we look at the shape of the spectrum, or more precisely at how the shape of the spectrum compare with the `diskbb` spectrum which is often use to fit spectral data.

Fig.4 shows that for low spin (blue points) the full GR simulated flux is relatively close to the `diskbb` flux that it is fitted against but as soon as we go to high spin the overall shape of the spectrum start to diverge. This would then lead to a worst χ^2 for higher spin than can be achieve for lower spin.

4 Conclusion

By combining smoothly two GR codes, one providing a full hydrodynamical solution and one providing the ray-tracing of the emission, we now have a fully functional numerical observatory which allows us to obtain spectrums and lightcurves of theoretical models with limited hypotheses. Further linking the output of NOVAs with SIXTE allows us to also test the capacity of new instruments to distinguish between models and explore new possibilities.

Among the numerous applications of NOVAs, we first looked at a way to test the efficiency of the fitting models commonly used and in particular we looked at how well the `kerrbb` model does constrain the spin. For our range of spin and accretion rates the `kerrbb` model performed well, in particular at high spin, and was able to get the spin within 0.1 of its actual value.

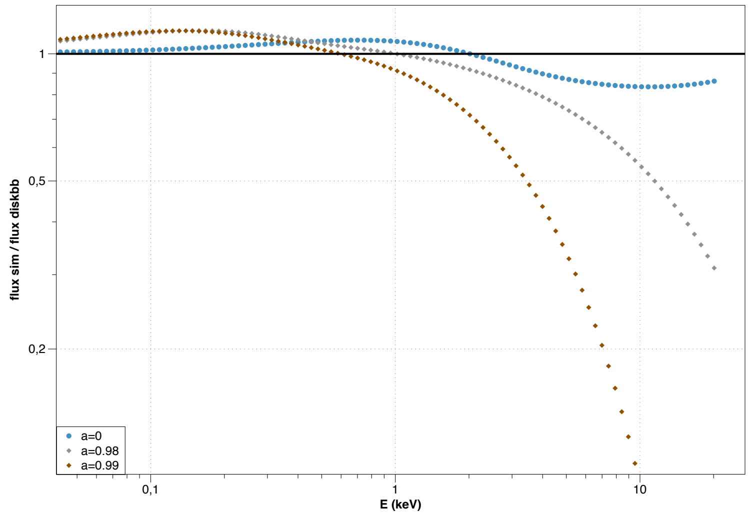

Figure 4. Evolution as function of energy of the simulated flux over the `diskbb` flux for the same system.

We also explore potential causes for the difficulty encountered when fitting high-spin system, and in particular the inability to obtain good χ^2. We found that the shape of the spectrum diverge from the model used to fit them as the spin increases, causing the fit to of lesser quality.

Acknowledgements

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