Gravitational Waves and GRBs from Tidal Disruption of Stars in the Center of Galaxies

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Abstract. Recent measurements by the Chandra satellite have shown that a supermassive black hole of $M = 2.6 \times 10^6 M_\odot$ is located in the Galactic Center; it seems probable from other observations that this fact is common in the majority of galaxies. On the other hand, GRB explosions are typical phenomena linked to galactic dynamics. In the present paper we discuss the possibility that GRBs are tidal disruption of stars by supermassive black holes located in the center of galaxies. This conjecture can be tested by a gravitational wave detector of the class of AURIGA.

INTRODUCTION

GRB engines are characterized by the following facts: 1) they are point-like sources of electromagnetic energy ($10^{51 \div 54}$ *erg*) comparable to that of a single galaxy; 2) they are always associated with a host galaxy (see ref. [1]). A plausible explanation can be found if there is a Supermassive Black Holes (SBH) in the Galactic Center with a mass of about 2×10^6 $M_\odot$ as it was recently discovered by satellite Chandra (see http://science.nasa.gov/headlines/y2000/ast29feb_1m.htm of Feb. 29, 2000). Moreover, it is very likely that the globular clusters have in their centers black holes with smaller masses.

The detailed study of the dynamics of the Galactic Center (see ref. [2]) points out that near the horizon of the SBH all the galactic objects are crushed by tidal disruption so that they can emit both electromagnetic and gravitational waves. For instance according to this view a GRB can be considered as the end of a star while it is swallowed by the SBH.

If this conjecture is correct, it should be possible to detect gravitational radiation by means of gravitational wave (gw) detectors using their directional sensitivity (antenna pattern) towards the candidate sources – either the Galactic Center or the center of nearby galaxies (M31, M84, M87, etc.) or the globular clusters. The basic idea is to separate the collected events recorded by a gravitational wave detector into the *"on source"* and *"off source"* sets depending on the sidereal hours when the detector is pointing toward a given source. The "off source" events will give an estimate of the background events (from unmodeled noise sources) while gw bursts can be detected as a mean excess of event energy in the "on source" set.

The paper is divided into two parts: in Section 2 we discuss some theoretical problems connected with the SBH model and in Section 3 we describe a method for the

measurement of gw emission from the Galactic Center by means of one or more gw detectors.

THEORETICAL PROBLEMS OF SBH

The paper by Ayal et al. [3] is very important because, in our opinion, it was the first attempt to calculate, using the 1PN approximation of General Relativity, what happens to a star falling into the SBH existing in the center of the Galaxy. However, these calculations are in some ways too rough, in particular:

1. An object like the sun is modeled as a polytropic fluid in a spherical configuration: only in this way it can be treated mathematically, but its physical structure is completely ignored.

2. Near a few Schwarzschild radii the classical mechanics break down and the system of a star and a black hole, which has well known obvious closed form solutions, has no relativistic closed form solution

3. The various approximations in general don't converge and the usual result is the appearance of divergences which make the two body problem mathematically intractable. These issues are covered in Chapter 9 of ref. [2]. Here we quote the main results. The singularities are of three kinds: i) a singularity in the density: stars cannot exist nearer than the horizon, and effectively they are destroyed before that point, either by collisions or by the SMB tidal field. In ref. [3] it is shown with explicit calculation that a polytropic sphere similar to the sun is destroyed at a distance of approximately $15R_{Sch}$ where R_{Sch} is the SMB horizon; ii) a singularity in the velocity which makes the dynamics mathematically intractable because of the Keplerian velocity divergency; iii) an optical singularity due to the fact that any mass bends light and, close to massive black hole and in small regions, some caustics appear, which cause the kinematics to be equally divergent.

4. Due to the severe limitation of the singularity of the calculations it is very difficult to believe the numbers put forth by Ayal et al. [3]. For instance, the energy emitted in gw is $\sim 1.6 \cdot 10^{46} erg$ and it could be underestimated by orders of magnitude. This value ensures that, on one hand the 1PN approximation holds and on the other the gravitational interaction is sufficiently strong to destroy the star. It should be noted that the energy converted in gw is calculated by the usual quadrupole formula and therefore, if it were possible to push the approximation closer to the black hole horizon, one would expect a greater gw emission.

Having made the above points, it would be highly desirable to pass directly to the measurement of gws, in order to test the various approximations and the effects of non-linearities in the mechanism of gw emission.

DESCRIPTION OF THE MEASUREMENT

The gravitational wave detector AURIGA, which is operating at the National Laboratories of Legnaro (Italy), is essentially an aluminum cylinder equipped with a resonant capacitive transducer which is coupled to a high sensitivity dc-squid amplifier [4]. Due
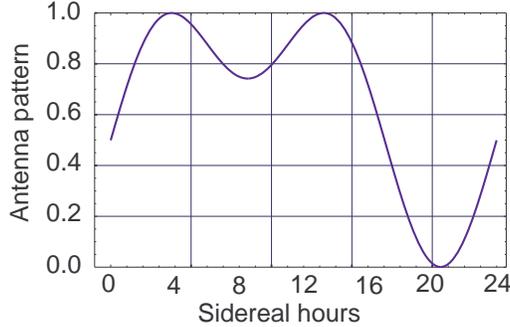

FIGURE 1. Relative sensitivity of the AURIGA detector towards the Galactic Center.

to the combination of the Earth's rotation and the antenna pattern, two times a day AURIGA is much more sensitive to the gw flux from the Galactic Center (see Figure 1). This particular combination happens at the same sidereal hours, when the Galactic Center direction is orthogonal to the detector symmetry axis. The modulation of the gw flux must have a period of one sidereal day with the two characteristic maxima of Figure 1 occurring at sidereal hours 4 and 13. This peculiar signature of the gw signals can be used to test if the conjecture we presented in the preceding Sections is true. In fact, the Galactic Center is the place where a high flux of gravitational waves should be emitted by stars and gas swallowed by the black hole. The cumulative counts of detected events should exhibit two peaks separated by 11 hours. If we collect data for a sufficiently long time (~ 100 sidereal days), we can form two distinct set of events: the "on source" set which collects all the events occurring around sidereal hours 4 and 13, and the "off source" sets corresponding to events around sidereal hour 20. The "off source" events will give an estimate of the background events (from unmodeled noise sources) while gravitational wave bursts (GWBs) can be detected as an excess of event energy (in average) for events belonging to the "on source" set.

The Mann–Whitney test, also known as the rank sum test or U–test [5], can be used to falsify the "null hypothesis" that the two populations "on" and "off" are identical, i.e. that the gw candidate events (belonging to the "on source" set) have the same mean energy $\langle E \rangle$ of background events (belonging to the "off source set"). The mean energy captured by the detector for the two sets can be expressed as

$$\langle E_{on} \rangle = \langle E_{off} \rangle + h_{RMS}^2 , \tag{1}$$

where h_{RMS}^2 is the averaged GWB amplitude associated with the activity of the Galactic Center. The sensitivity of the search depends on three main factors [6], namely: i) the minimal GWB amplitude detectable at unit signal-to-noise ratio $h_{min} \equiv (\tau_s \; (\int_{-\infty}^{+\infty} 1/S_h(\nu)d\nu)^{-1/2}$, where τ_s is the duration of the GWB ($\sim 1 \; msec$) and $S_h(\nu)$ is the power spectral density of the noise expressed in terms of gravitational

wave amplitude at the detector input; ii) the event search threshold, usually set to $5 \times h_{min}$ and iii) the number of the events in the "on" and "off" sets, N_{on} and N_{off} respectively.
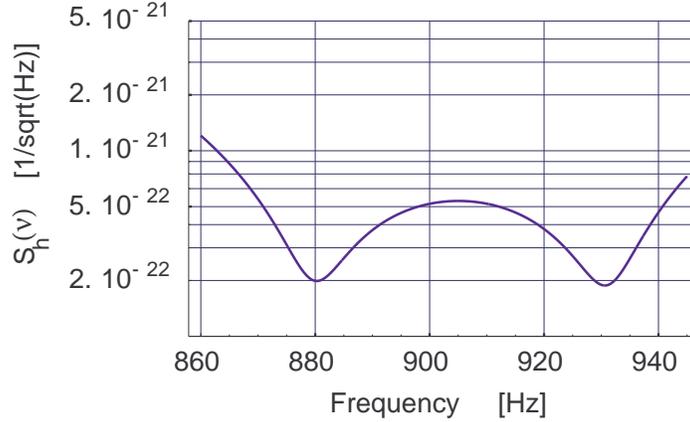

FIGURE 2. Power spectral density of the AURIGA noise expressed in terms of gravitational wave amplitude at the detector input.

A similar technique has been applied by our group (see ref. [6] and [7]) to test if there exists a concomitant emission of GRBs and gw bursts. Unfortunately, as most GRBs are at cosmological distances, the AURIGA sensitivity ($h_{min} \sim 10^{-19}$) and duty cycle ($N_{on} \approx 100$) were not sufficient to detect any positive effect. However, in the present paper we limit our analysis at the distance of the Galactic Center (i.e. $\sim 8\ kpc$), and so the probability to detect GWBs is higher.

In addition, the new experimental setup of AURIGA [4] promises an increase of its sensitivity and bandwidth as reported in Figure 2, which translates into a burst sensitivity of $h_{min} \sim 10^{-20}$. The same procedure can be applied to the events in coincidence among two or more parallel detectors. To conclude we must recall that the group of Rome have already tried to detect GWBs coming from the galactic plane (see ref. [8] and the subsequent criticism in ref. [9]).

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