GRAVITATIONAL WAVES FROM COLLAPSING GLOBULAR CLUSTER SYSTEMS

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ABSTRACT. The evolution of globular cluster systems in some galaxies can be cause of merging of globulars in the very central regions. This high stellar density favours the growth of a central nucleus via swallowing of surrounding stars. The infall of stars into a nuclear black hole is here shown to be, under certain conditions, not only source of electromagnetic radiation but also a significant source of gravitational waves.

1. Introduction

Many theoretical and observational arguments (Capuzzo–Dolcetta & Vignola, 1997; Capuzzo–Dolcetta & Tesserì, 1997; Capuzzo–Dolcetta, 1998; Capuzzo–Dolcetta & Miocchi, 1998) strongly support the hypothesis raised and discussed first in Capuzzo–Dolcetta (1993) that the AGN powering can be, at least in some galaxies, the energy subtracted to the gravitational field in form of stars belonging to a dense stellar environment that are swallowed by the central massive black hole.

The dense stellar environment around the galactic nucleus is formed by globular clusters orbitally decayed to the central galactic regions due to dynamical friction, and there partly merged and partly tidally destroyed. The mass falling into the nucleus goes both to enhance its mass and into radiation. The process of matter infall corresponds to a non–radially symmetrical nucleus accretion and so implies gravitational waves emission, too. Here we give a preliminary estimate of the number of gravitational bursts that the space–based interferometer LISA (at present under development by ESA) should detect.

2. Gravitational waves from accreting galactic nuclei

It is known (see Davis & Ruffini, 1971) that a point mass \( m \) in radial free fall into a black hole of mass \( M \) emits an impulse of gravitational waves whose total energy is \( E \sim 0.01(m/M)mc^2 \).

It can be easily shown that the gravitational wave spectrum peaks at the frequency

\[
f_0 \sim 0.05 \frac{c^3}{GM}(z+1) \sim \frac{10^4}{M(M_\odot)(z+1)} \text{ (Hz),}
\]

(1)
and that the amplitude of the associated metric perturbation is
\[ h \sim \frac{0.49}{d} \left( \frac{Gm}{c^2} \right), \quad (2) \]
where \( d \) is the distance of the source and \( z \) its red–shift.

If the radius of the falling star, \( R \), is very small compared with the wavelength of the gravitational waves emitted (of the order of the black hole Schwarzschild’s radius) then the star can be actually treated as a point mass, and disruptive interference phenomena can be neglected (see Haugan, Shapiro & Wasserman, 1982 for more details).

Flanagan & Hughes (1997) give the analytic approximation for the expected noise fluctuation curve \( h_N(f) \) for the interferometer LISA, showing that the frequency range of acceptable gravitational waves detection is \( 10^{-4} \div 10^{-1} \) Hz. A necessary condition for an impulse to be detected is:
\[ S_N \equiv \frac{h}{h_N(f_0)} > 1. \quad (3) \]
where \( S_N \), by definition, is the signal–to–noise ratio. The condition on the star radius together with (1), (2) and (3) reflect into the following constraints involving the black hole mass and the distance of the source:
\[ M > 6.7 \cdot 10^8 \frac{R^{9/8}}{m^{1/8}} (M_\odot), \quad (4) \]
\[ d < 2.4 \cdot 10^{-14} \frac{m}{h_N(f_0)} \text{ (pc)}, \quad (5) \]
where \( R \) and \( m \) are expressed in solar units.
To give a global evaluation of the signal detectable it is necessary, of course, to integrate over all the possible sources, i.e. to cumulate the contribution of all the stars falling into the galactic central black holes in galaxies at any red–shift.

3. Gravitational wave impulses from high density galactic central regions

As shown firstly by Capuzzo–Dolcetta (1993), dynamical friction and tidal disruption are effective mechanisms for globular cluster system (GCS) evolution in galaxies. As a result, a globular cluster loses energy and angular momentum, approaching more and more to the central regions where, eventually, they can merge and grow a ‘super cluster’ and, also, may lose their identity as a cluster due to a strong tidal interaction with a compact central nucleus.

Capuzzo–Dolcetta (1993, 1998) computed a series of models of evolution of GCSs in a triaxial external potential, taking into account collective effects (dynamical friction and tidal interaction) to follow the mass loss to the galactic centre and its contribution to the galactic nucleus feeding and growth. We do not deep here the details and characteristics of these models, but just say that we refer to a model where: (i) the nucleus is initially absent; (ii) the GCS system is composed by 1,000 globular clusters of the same mass,
$M_{bc} = 10^6 M_\odot$; (iii) the clusters are moving on box orbits with a velocity dispersion about 300 km/sec. The formation and evolution of a central compact object is followed in detail: for what of interest here, we need just the quantities $\dot{M}(t)$ and $M(t)$, i.e. the GCS mass loss and nucleus mass as functions of time.

We transformed the time dependences into red–shift dependences assuming an Einstein–De Sitter universe and noted that an almost constant value of $M$ is reached at $z \approx 0.35$, near to the peak of $\dot{M}$, for an assumed red–shift of galaxy formation $z_f = 5.5$. This, together with eq. (1), tells us that sources closer than $z \approx 0.35$ (that is 1 Gpc) do not contribute to gravitational wave signal because they correspond to too massive nuclei, $M > 10^8 M_\odot$ and generate impulses with $f_0$ outside the ‘optimal’ $10^{-3} \div 10^{-2}$ Hz band. This implies a value of $m \geq 20 M_\odot$.

For this reason we have to deal with massive stellar remnants, only.

Fig. 1. Number of impulses per year that LISA should detect as a function of $H_0$ and $z_f$ the red-shift of galaxy formation.

We assume such remnants to be compact objects with $R << 1 R_\odot$ and $< m_r >= 30 M_\odot$. The ratio of the number of these remnants to the total, $w$, is computed assuming a Salpeter’s mass function ($\psi(m) \propto m^{-2.35}$). Given the number density of sources $n(z) = n_0(1 + z)^3$, i.e. the density at red-shift $z$ of galaxies presumed to have a central black hole, and given the accretion rate $\dot{M}(z)$, the number of events per unit time is
just:

\[ N = w \int_{0}^{\infty} \frac{\dot{M}(z)}{<m_r>} \Theta(z)n(z)\Gamma(z)dz, \]  

where

\[ \Theta(z) = \begin{cases} 
1, & \text{if conditions (4) and (5) are satisfied} \\
0, & \text{otherwise,}
\end{cases} \]

and \( \Gamma(z)dz \) is the shell volume element.

According to our estimate, LISA should detect up to some hundreds events per year, depending on the value of the Hubble constant and on the red-shift of galaxies formation \( z_f \) (see Fig. 1). This latter represents the origin of time by which the AGN fueling starts to work.

4. Conclusions

The GCS evolution is responsible for AGN activity and, moreover, the infall of compact stellar remnants into the active central galactic black hole is source of gravitational waves. These gravitational waves may be detect by the ESA space gravitational wave interferometer LISA which will be launched within year 2010. The number of detectable events per year is of the order of hundreds.

Our future aim is to improve the present treatment by considering also the inspirdling of remnants towards the black hole and, by means of a Fourier analysis of the impulses emitted, we wish to be able to distinguish the kind of gravitational wave emission studied here from the background of gravitational waves detected.

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