Multi-band Astronomy with LISA

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Abstract. We discuss astrophysical scenarios relevant to the generation of gravitational waves (GW) and effects expected to arise from the interaction of GW and electromagnetic (EM) radiation. A strong programme of coordinated GW and EM astrophysical studies must be established in order to ensure the exploitation of the full scientific potential of the LISA mission. We describe on-going astrophysical work, and suggest alternative approaches to current studies, which are relevant to these considerations.

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INTRODUCTION

LISA will return unprecedented data on GW sources; however, its full scientific potential will be realised only by matching the sources with astrophysical counterparts and correlating their properties over the EM spectrum. Different types of sources require different approaches: direct identification with known EM sources in some cases (like for ultra-compact binaries), and statistical estimation from the systems EM characteristics in others (such as for rates of Super Massive Black Hole, or SMBH, mergers, and Extreme Mass Ratio Inspirals, or EMRIs). In turn, knowledge of the EM properties (e.g. for the ultra-compact binaries) will be crucial in constructing accurate waveforms to aid LISA’s signal processing. The consequences of the interaction between GW and EM radiation may also have important implications, for instance on events such as gamma-ray bursts. It is clear that a large degree of synergy is needed between the GW and EM astrophysical communities, in order to build a strong programme of coordinated studies targeted to the needs of LISA. Below we discuss on-going astrophysical work relevant to such ideas.

ULTRA-COMPACT BINARIES

Ultra-compact binaries with white dwarf secondaries are predicted to be both numerous and strong GW sources. Indeed, these binaries will be the so-called Verification Binaries for LISA. The effects of gravitational radiation can be observed directly in the two candidate ultra-compact binaries RX J0806+15 (binary orbit 321 sec) and RX J1914+24
FIGURE 1. Left: In the UI model (sketch from [2]), large electrical currents are driven as a conducting body (the secondary white dwarf) orbits a magnetic body (the primary white dwarf): these currents are dissipated at foot-points on the primary. The currents are so powerful that emission occurs in the X-ray band - the X-rays irradiate the secondary white dwarf and give rise to the anti-phase between X-ray and optical lightcurves [4]. Right: Power of electrical dissipation (solid lines) and GW (dotted) from UI systems with 9.5 min orbital period (cf. RXJ1914+24). Curves a, b, c and d correspond to systems with a 0.5, 0.7, 1.0 and 1.3 solar mass primary magnetic white dwarf (figure from [2]).

(569 sec). If these periods can be verified as being signatures of their binary orbital period, then observational work has shown that both systems are spinning up, i.e. their orbit is shrinking. Recent work indicates that RX J0806+15 should be detectable using LISA in less than one week [1]. However, the exact mechanism which powers the EM emission in these candidate systems has not been settled. The proposed models fall into two general categories - accretion-powered and non-accretion-powered. The non-accretion model is that of the so-called Unipolar Inductor (UI; see Fig. 1, left) [2]. Although still a matter of some debate, this model perhaps comes closest to predicting the observational properties of RX J0806+15 and RX J1914+24 (e.g. [3]). The EM properties of the other known ultra-compact systems (orbital periods between ∼10 and 70 min) imply that they are powered by accretion.

Determining the mechanism which powers the EM emission is crucial in interpreting the observed spin-up rates seen in both RXJ0806+15 and RX J1914+24 [5, 3]. If UI is powering the EM emission, then their orbital evolution is determined jointly by gravitational radiation losses and EM interactions (Fig. 1, right) [6]. Only by knowing the relative proportion that each mechanism contributes to the spin-up can we correctly predict their GW signal.

There are reasons to expect that UI could operate in other binary systems, including a white dwarf orbiting a rotating black hole. This would affect the system’s orbital evolution and hence the expected gravitational signal. The question is: How many systems are there? White dwarf - white dwarf binaries are expected to make a significant contribution to the background gravitational signal in the LISA passband. Correctly modelling this background signal is essential for accurately predicting the sensitivity of LISA observations. Theoretical models of stellar populations and binary evolution suggest that interacting white dwarf - white dwarf binaries are common place in our Galaxy. However, less than 20 of such interacting binaries are known. Currently it is not
clear whether this discrepancy is due to inadequacies in the theoretical models or that many more interacting binaries await discovery.

A number of projects are on-going to test this question by searching for new systems. The SPY project (Sn Ia Progenitor surveY), for instance, searches for radial velocity variations in a large sample of faint white dwarfs [8]. The aim is to determine the orbital period distribution of such binaries and also test whether these systems can give rise to type Ia supernovae. A different approach is provided by RATS (RApid Temporal Survey) [9]. This study searches for stellar sources whose intensity varies on short periods, from a few minutes to periods longer than several hours. A pilot field included the binary RX J0806+15 (321 sec orbital period): such kind of system can easily be detected (Fig. 2). RATS is on-going but initial results suggest that theoretical models significantly overestimate the space density of interacting white dwarf - white dwarf binaries.

SUPER MASSIVE BLACK HOLES (SMBHS) AS GW SOURCES

Predictions of event rates of both, SMBH binary mergers and EMRIs are heavily dependent on the universal mass density distribution of SMBHs. A strong correlation has been established between SMBH mass and galactic velocity dispersion (and a weaker one with luminosity of the host galaxy’s stellar bulge). The correlation has been used to derive the local SMBH mass density. The AGN luminosity function as a function of redshift, i.e. the representation of their evolution with cosmic time, traces the accretion history of the BH and gives a measure of the accreted mass density, and ultimately the mass distribution of SMBHs [10]. Such calculations have been based so far on the luminosity function of optically bright QSOs.

However, a discrepancy exists between the strong optical evolution of AGN at $z \lesssim 2$, and the X-ray luminosity function which peaks at $z \sim 1$. The existence of a significant number of absorbed AGN making up a large fraction of the entire population may explain this inconsistency. Deep pencil-beam X-ray surveys of AGN appear to indicate that the amount of obscuration is strongly luminosity-dependent, with the fraction (>
FIGURE 3. 2–10 keV intrinsic rest-frame luminosities as a function of redshift for AGN detected with XMM-Newton in the 13H deep field. Sources which show absorption in their X-ray spectra are indicated by filled rectangles, while those without significant X-ray absorption are shown by triangles.

75% of obscured AGN being larger at low luminosities.

On the other hand, XMM-Newton large area surveys [11] show that the pattern of absorption in AGN is independent of both redshift and luminosity, with obscured AGN being ∼3 times more populous than un-obscured ones at all redshifts and luminosities. This is illustrated by the presence of absorbed objects (filled rectangles) in a $L_X - z$ plot (Fig. 3) [12].

Moreover, the space density of X-ray selected AGN has been found to be up to a factor of 40 larger than that of bright optically selected QSOs [13]. These results require that estimates of the SMBH mass distribution be reconsidered.

Our knowledge of the demographics and evolution of AGN, and thus the accuracy of the SMBH mass distribution, is bound to improve further as we plan to combine the wide angle, deep XMM-Newton surveys with mid-infrared (Spitzer) imaging surveys, which have the potential of revealing the most distant and heavily absorbed AGN.

GAMMA-RAY BURSTS (GRB’S)

The detection by Swift of more than 120 GRBs so far (mid 2006) has already revolutionised our view of these most energetic phenomena, which are thought to be associated with the coalescence of neutron stars and black holes, and thus GW production. As statis-
tics improve with more bursts being detected, the characterisation of larger samples of short (< 2 sec) and long bursts will provide an estimate of the relative frequency of the different types of mergers, be coalescent neutron stars, black hole mergers or hypernova events.

PHOTON ENERGY UP-SHIFT BY PLASMA WAVES INDUCED BY GW FROM A COMPACT SOURCE

The highly non-linear nature of GW at source results in the coupling to other wave modes such as plasma waves. The generation of these wave modes causes an attenuation of the GW. For strong GW burst models the Bondi-Sachs metric has been used to evaluate the non-linear modification of the effective refractive index. These models show that photons and high-energy particles can experience significant energy shifts by ’surfing’ on the plasma waves [14]. This effect may have important implications on gamma-ray events such as GRBs and causal GW and EM observations.

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