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The GEO 600 Gravitational Wave Detector – Pulsar Prospects

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Abstract. The GEO 600 laser-interferometric gravitational wave detector near Hannover, Germany, is one of six such interferometers now close to operation worldwide. The UK/German GEO collaboration uses advanced technologies, including monolithic silica suspensions and signal recycling, to deliver a sensitivity comparable with much larger detectors in their initial configurations. Here we review the design and performance of GEO 600 and consider the prospects for a direct detection of continuous gravitational waves from spinning neutron stars.

1. Introduction

The world-wide effort to detect gravitational waves directly has resulted in the construction of a network of laser interferometers. The US LIGO project (Sigg 2002) contributes three instruments, and the French-Italian VIRGO detector (Acernese et al. 2002), the TAMA 300 detector in Japan (Kuroda et al. 2002) and the UK/German GEO 600 detector (Willke et al. 2002) one each. These detectors are based on the principles of Michelson interferometry and use two long orthogonal arms to form a quadrupole antenna sensitive to gravitational waves, although the design details vary considerably between detectors.

The GEO 600 detector at Ruthe (close to Hannover, Germany) is now nearly complete and has recently carried out its first science observations. These were performed in coincidence with the LIGO detectors as part of its role within the LIGO Science Collaboration (LSC).

2. Interferometer design and performance

GEO was constructed on a site that restricted its arm lengths to 600 m, so considerable effort was put into its mechanical and optical design to reach the desired sensitivity. Seismic disturbances and thermal motions of the mirrors and of other optical components introduce changes in the optical path lengths along the two arms and add noise to the differential strain, h, caused by a passing gravitational wave. To minimise this the entire optical path, including the 60 cm diameter tube arms, is held at high vacuum ($\sim 10^{-9}$ mbar), and materials capable of significant outgassing are sealed in steel or glass.

The calibrated strain output of the detector has many contributing noise components, each with a characteristic spectral density. Below about 40 Hz the spectrum is dominated by seismic noise, and seismic isolation is provided by passive stainless steel and rubber stacks supporting double or triple pendulum suspensions holding the optical components (Plissi et al. 2000). The beam splitter, end mirror optics and lower suspensions are made of fused silica, suspended by 270 μm diameter fused silica fibres, joined with welds and hydroxy-catalysed bonds (Rowan et al. 1998). These high-strength bonds preserve the homogeneity of the silica and give the lower assemblies mechanical quality factors in excess of 10^7 (Cagnoli et al. 2000). At frequencies above about 400 Hz the dominant spectral noise power is from laser shot noise, whilst at intermediate frequencies the spectrum is dominated by the thermal and thermo-refractive noise intrinsic to silica (Braginsky, Gorodetsky & Vyatchanin 2000).

Further noise can be introduced by laser fluctuations or changes in optical alignment causing modulation of the light power at the interferometer's output port. The laser system is built around a master non-planar ring oscillator that is injection-locked to a diode-pumped Nd:YAG slave laser delivering 12 W at 1064 nm. The light is fed to two sequential mode-cleaners that temporally and spatially filter the beam and seismically isolate it. The Michelson interferometer is held on a dark fringe at its output port, and configured as a resonant cavity by inserting a power recycling mirror at the input port. This builds up the effective power at the beam splitter to several kilowatts and so improves the shot-noise limited sensitivity of the instrument.

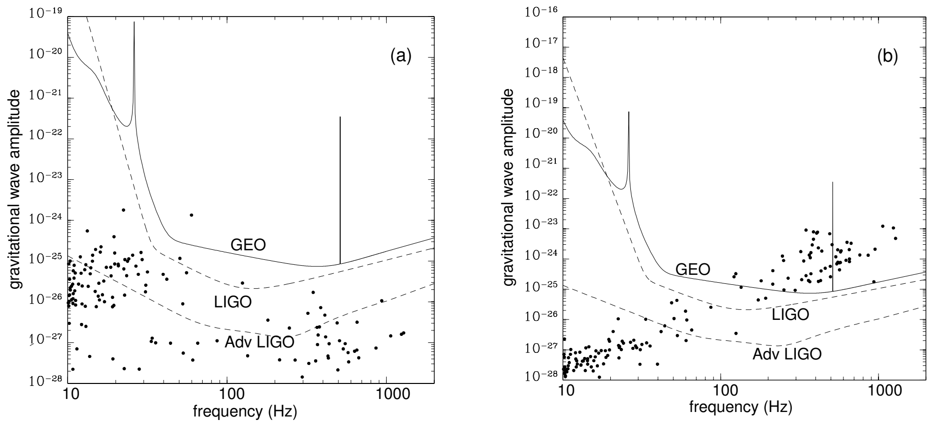

Figure 1. Theoretical strain signals from known pulsars after one year of integration, (a) attributing the rate of loss of rotational kinetic energy to gravitational luminosity and (b) assuming an equatorial ellipticity of 10^{-5}. The one-year theoretical sensitivities for GEO, LIGO and Advanced LIGO are also shown.

Although the detector is intrinsically broadband we can trade bandwidth for sensitivity by 'signal recycling' (Meers 1988). When installed, this will increase the shot-noise limited sensitivity by a factor of about 10 around a chosen frequency and promises to be of particular importance for targeted observations of low-mass X-ray binaries (Bildsten, these proceedings).

3. Observing programme

The sensitivity of GEO (and of all the current generation of detectors) is such that the probability of an astrophysical detection is fair. We will have to wait until Advanced LIGO before the odds become well stacked in our favour. However the prospect of a detection is very real, and specific effort has gone into optimal strategies for detecting the chirp waveforms from black-hole/black-hole inspirals, burst signals coincident at several detectors, the stochastic gravitational wave background and signals from continuous wave sources such as pulsars.

We expect a non-precessing neutron star of equatorial ellipticity ϵ spinning at a frequency ν_0 to produce a strain amplitude, h_0, a distance r away of

$$h_0 = \frac{16\pi^2 G}{c^4}\frac{I_{zz}\nu_0^2}{r}\epsilon, \tag{1}$$

where I_{zz} is the principal moment of inertia about the rotation axis, G is the gravitational constant and c the speed of light (e.g., Brady 1998). It is interesting to note that because our detection is coherent, the signal strength falls off with distance only as $1/r$. The interferometer has antenna response patterns, F_+ and $F_\times$, to the '+' and '$\times$' wave polarisations. For a given source, these antenna responses depend both on time, t, (this is a transit instrument) and on the polarisation angle of the source (ψ, loosely its position angle around the line of sight), so the detected strain signal is quasi-sinusoidal and of the form

$$h(t) = \frac{1}{2}F_{+}(\psi, t)h_0(1 + \cos^2 \iota)\cos 2\Phi(t) + F_{\times}(\psi, t)h_0 \cos \iota \sin 2\Phi(t), \qquad (2)$$

where ι is the angle between the spin axis and the line of sight, and $\Phi(t)$ is the observed rotational phase ($\simeq 2\pi\nu_0 t$) (e.g., Jaranowski et al. 1998). The detector has a quadrupole response to each polarisation, and the Earth is transparent to gravitational waves, so nearly the whole celestial sphere is under observation at any one time. The largest uncertainties in the expected strain signal are the neutron star's equatorial ellipticity and, for radio-quiet neutron stars, their distances and frequencies. We can see from Figure 1 and Equation 1 that millisecond pulsars represent some of our best candidates for a direct detection. Predicted sensitivities require a millisecond source at 10 kpc to have an ellipticity of $\sim 10^{-6}$ (a quadrupole moment of $\sim 10^{39}\,\mathrm{g\,cm^2}$) for detection after one year. However the gravitational luminosity would need to come from a source somewhat better than the observed rate of decrease of rotational kinetic energy for these objects (Figure 1a), if we take them to be isolated and effectively rigid rotators.

4. The future

Both GEO and LIGO are presently on their final commissioning phases, and are expected to be working at full sensitivity by 2003. Members of GEO and LIGO are already working within the LSC to share software and data. Present pulsar-related efforts in GEO are concentrating on targeted searches for emission from known radio pulsars, although the algorithmic and computational resources needed to carry out more general all-sky searches are well advanced.

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