THE DETECTION OF GRAVITATIONAL WAVES.

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Abstract

Gravitational waves, one of the more exotic predictions of Einstein's General Theory of Relativity, may, after 80 years of controversy over their existence, be detected within the next decade. Sources such as coalescing compact binary systems, stellar collapses and pulsars are all possible candidates for detection. The most promising design of gravitational wave detector, offering the possibility of very high sensitivities over a wide range of frequency, uses test masses a long distance apart and freely suspended as pendulums on earth or in drag free craft in space; laser interferometry provides a means of sensing the motion of the masses produced as they interact with a gravitational wave. The main theme of this paper will be a review of the mechanical and optical principles used in the various long baseline systems being built around the world - LIGO (USA), VIRGO (Italy/France), TAMA300 (Japan) and GEO600 (UK/Germany) - and in LISA, a proposed space-borne interferometer.

1. INTRODUCTION

Gravitational Waves, predicted by General Relativity to result from the non-symmetrical acceleration of mass, may be directly detected within the next decade. Construction of a worldwide system of the largest optical interferometers ever to be built on earth (LIGO Project, USA [1], VIRGO Project, Italy/France [2], GEO 600 Project, Germany/UK [3] and the TAMA 300 Project, Japan [4]) is proceeding vigorously, and this detector array should have the capability of detecting gravitational wave signals from violent astrophysical events in the Universe.

Some early relativists were sceptical about the existence of gravitational waves however their reality is no longer in doubt. Indeed the evolution of the orbit of the binary pulsar, PSR 1913 +16, can only be explained if angular momentum and energy is carried away from this system by gravitational waves [5], and the 1993 Nobel Prize in Physics was awarded to Hulse and Taylor for their experimental observations and subsequent interpretations of this system [6,7].

Gravitational waves are produced when matter is accelerated in an asymmetrical way; but due to the nature of the gravitational interaction, significant levels of radiation are produced only when very large masses are accelerated in very strong gravitational fields. Such a situation cannot be found on earth but is found in a variety of astrophysical systems.

Gravitational wave signals are expected over a wide range of frequencies; from ~10^{-17}Hz in the case of ripples in the cosmological background to ~10^{3}Hz from the formation of neutron stars in supernova explosions. The most predictable sources are binary star systems. However there are many sources of much greater astrophysical interest associated with black hole interactions and coalescences, neutron star coalescences, stellar collapses to neutron stars and black holes (supernova explosions), pulsars, and the physics of the early Universe. For a full discussion of sources refer to the material contained in reference [8].

Why is there currently such interest worldwide in the detection of gravitational waves? Partly because observation of the velocity and polarisation states of the signals will allow a direct experimental check of the wave predictions of General Relativity; but more importantly because the detection of the signals will allow access to an as yet untapped source of information about astrophysical processes including these mentioned above. It is interesting to note that the gravitational wave signal from a coalescing compact binary star system has a relatively simple form and the distance to the source can be obtained from a combination of its signal strength and its evolution in time; if the redshift at that distance is found, Hubble's Constant - the value for which has been a source of lively debate for many years - may then be determined with a high degree of accuracy [9].

2. DETECTION OF GRAVITATIONAL WAVES

Gravitational waves are most simply thought of as ripples in the curvature of space-time, their effect being to change the separation of adjacent masses on earth or in space; this tidal effect is the basis of all present detectors. The problem for the experimental physicist is that the predicted magnitudes of the strains in space caused by gravitational waves are of the order of 10^{-21} or lower [6]. Indeed current theoretical models suggest that in order to detect a few events per year – from coalescing Neutron star binary systems for example – sensitivity close to 10^{-22} is required. Signal strengths at the earth for a number of sources are shown in Fig. 1.

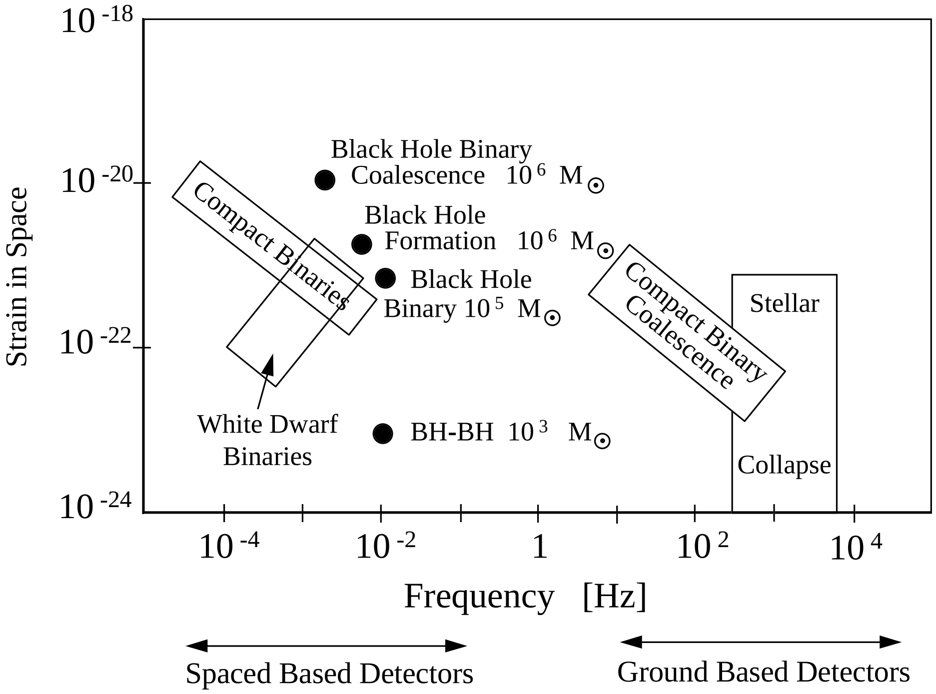

Fig. 1. Some possible sources for ground based and space-borne detectors

The small signal levels mean that limiting noise sources resulting from the thermal motion of molecules in the detector (thermal noise), from seismic or other mechanical disturbances, and from noise associated with the detector readout, whether electronic or optical, must be reduced to a very low level. For signals above ~10Hz ground based experiments are possible, but for lower frequencies where local fluctuating gravitational gradients and seismic noise on earth become a problem, it is best to consider developing detectors to be used in space [10].

2.1 Initial Detectors and their Development

The earliest experiments in the field were ground based and were carried out by Joseph Weber of the University of Maryland about 30 years ago. Having looked for evidence of excitation of the normal modes of the earth by very low frequency gravitational waves [11], Weber then moved on to look for tidal strains in aluminium bars which were at room temperature and were well isolated from ground vibrations and acoustic noise in the laboratory [12,13]. The bars were resonant at 1600Hz, a frequency where the energy spectrum of the signals from collapsing stars was predicted to peak. Despite the fact that Weber observed coincident excitations of his detectors placed up to 1000km apart, at a rate of approximately one event per day, his results were not substantiated by similar experiments carried out in several other laboratories in the USA, Germany, Britain and Russia. It seems unlikely that Weber was observing gravitational wave signals because, although his detectors were very sensitive, being able to detect strains of the order of 10^{-15} over millisecond timescales, their sensitivity was far away from what was predicted to be required theoretically. Development of Weber bar type detectors has continued with the emphasis being on cooling to reduce the noise levels, and currently systems at the Universities of Rome [14], Louisiana [15] and Perth (Western Australia) [16] are achieving sensitivity levels better than 10^{-18} for millisecond pulses. Bar detectors have a disadvantage, however, of being sensitive only to signals that have significant spectral energy in a narrow band around their resonant frequency.

2.2 Long Baseline Detectors on Earth

An alternative and very flexible design of gravitational wave detector offers the possibility of very high sensitivities over a wide range of frequency [1-4].

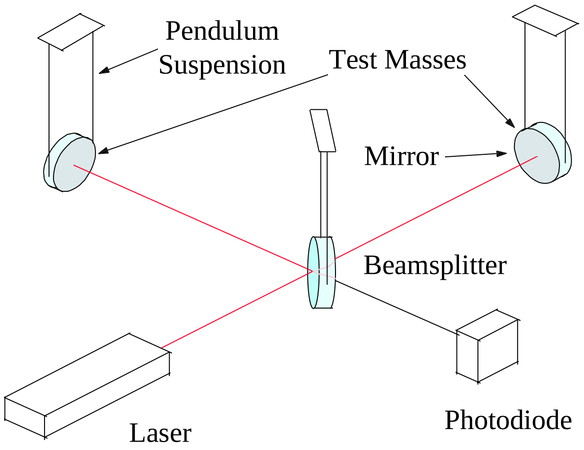

Fig.2 Schematic of gravitational wave detector using laser interferometry

This uses test masses a long distance apart and freely suspended as pendulums to isolate against seismic noise and reduce the effects of thermal noise; laser interferometry provides a means of sensing the motion of the masses produced as they interact with a gravitational wave (Fig.2). This technique is based on the Michelson interferometer and is particularly suited to the detection of gravitational waves as they have a quadrupole nature. Waves propagating perpendicular to the plane of the interferometer will result in one arm of the interferometer being increased in length while the other arm is decreased and vice versa. This results in a small change in the interference pattern of the light observed at the interferometer output. A typical design specification to allow a reasonable probability for detecting sources is to achieve a noise floor in strain smaller than $2 \times 10^{-23}/\sqrt{Hz}$. The distance between test masses possible on earth is limited to a few km by geographical and cost factors. If we assume an arm length of 3km the above specification sets the requirement that the residual motion of each test mass is smaller than 3×10^{-20} $m/\sqrt{Hz}$ over the operating range of the detector, which may be from ~10Hz to a few kHz, and requires that the optical detection system at the output of the interferometer must be good enough to detect such small motions.

2.3 Noise Sources which limit the Sensitivity of Interferometric Gravitational Wave Detectors

Fundamentally it should be possible to build systems using laser interferometry to monitor strains in space which are only limited by the Heisenberg Uncertainty Principle; however there are other practical issues which must be taken into account. Fluctuating gravitational gradients pose one limitation to the interferometer sensitivity achievable at low frequencies and it is the level of noise from this source which dictates that experiments to look for sub-Hz gravitational wave signals have to be carried out in space [17,18]. In general for ground based detectors the most important limitations to sensitivity are a result of seismic and other ground-borne mechanical noise, thermal noise associated with the test masses and their suspensions and shot noise in the photocurrent from the photodiode which detects the interference pattern. The significance of each of these sources will be briefly reviewed.

2.3.1 *Seismic Noise*

Seismic noise at a reasonably quiet site on the earth follows a spectrum in all three dimensions close to $10^{-7}/f^2$ $mHz^{-1/2}$ and thus if the motion of each test mass has to be less than $3 \times 10^{-20} m/\sqrt{Hz}$ at a frequency such as 30Hz then the level of seismic isolation required at 30Hz in the horizontal direction is greater than 10^9. Since there is liable to be some coupling of vertical noise through to horizontal a significant level of isolation has to be provided in the vertical direction also. Thus the suspension systems for the test masses must be carefully designed to have this order of seismic isolation. Such isolation can be provided in a relatively simple way; e.g. by suspending each test mass as the last stage of a multiple pendulum system which itself is hung from a plate mounted on passive ‘rubber’ isolation mounts or on an active (electro-mechanical) anti-vibration system. The multiple pendulum system also has to be soft in the vertical direction to allow vertical isolation.

2.3.2 *Thermal Noise*

Of the many noise sources which may degrade the sensitivity of ground based laser interferometric gravitational wave detectors, thermal noise associated with the mirror masses and the last stage of their suspensions is likely to be the most significant at the lower end of the operating range of the detector [19]. The operating range of the detector lies between the resonances of the test masses and their pendulum suspensions, and thus it is the thermal noise in the tails of the resonant modes which is important. In order to keep the off-resonance thermal noise as low as possible the mechanical loss factors of the material of the test masses and of the fibres or wires used to suspend the test masses need to kept low. This is achieved if the mechanical quality factors of the masses and pendulum resonances are as high as possible. Indeed, to achieve the level of sensitivity discussed above the quality factor of the test masses (~15-20kg) must be ~ 3×10^7 and the quality factor of the pendulum resonances should be greater than 10^8. Discussions relevant to this are given in [20]. These are very high quality factors and they put significant constraints on the choice of material for the test masses and the suspending fibres as well as demanding that very low loss jointing techniques of the fibres to the masses be used. One viable solution is to use fused silica masses hung by fused silica fibres [21,22] although the use of other materials such as sapphire may be possible [23,20].

2.3.3 *Photoelectron Shot Noise*

As mentioned earlier it is very important that the system used for sensing the optical fringe movement on the output of the interferometer can sense strains in space of $2 \times 10^{-23}/\sqrt{\text{Hz}}$ or differences in the lengths of the two arms of less than 10^{-19}m, a minute displacement compared to the wavelength of light ~ 10^{-6}m. The limitation is set by shot noise in the detected photocurrent and from consideration of the number of photoelectrons measured in a time τ it can be shown that the detectable strain sensitivity depends on the level of laser power (I_0) of wavelength λ used to illuminate the interferometer of arm length L, and on the time τ, such that:

$$\text{Detectable strain in time } \tau \quad = 1/L\,[\lambda hc/4\pi^2 I_0\tau]^{0.5}$$

$$\text{or Detectable strain}/\sqrt{\text{Hz}} \quad = 1/L[\lambda hc/2\pi^2 I_0]^{0.5}$$

where c is the velocity of light.

Thus achievement of the required strain sensitivity level requires a laser, operating at a wavelength of 10^{-6} m, to provide 3×10^6 W power at the input to the interferometer. This is a formidable requirement.

However the situation can be helped greatly if a multipass arrangement is used in the arms of the interferometer as this multiplies up the apparent movement by the number of bounces. The multiple beams can either be separate as in an optical delay line, or may lie on top of each other as in a Fabry-Perot resonant cavity as shown in Fig. 3.

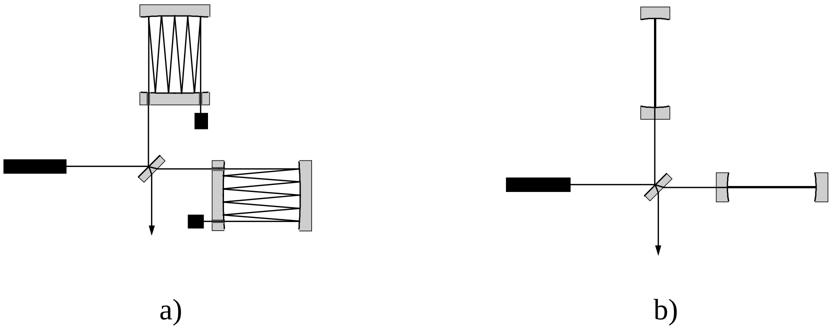
a) b)

Fig.3. Michelson Interferometers with (a) delay lines and (b) Fabry-Perot cavities in the arms of the interferometer.

The number of bounces is set by the fact that the light should not stay in the arms longer than the characteristic timescale of the signal - otherwise some cancellation of the detected signal may occur. Thus if signals of characteristic timescale 1msec are to be searched for the number of bounces should not exceed 50 for an arm length of 3km. With 50 bounces the required laser power is reduced to 1.2 x 10^3W, still a formidable requirement.

It can be shown that the optimum signal to noise ratio in a Michelson interferometer is obtained when the arm lengths are such that the output light is very close to a minimum. (This is not intuitively obvious and is discussed more fully in [24]). In this situation if the mirrors are of very low optical loss, nearly all of the light, which is supplied to the interferometer, is reflected back towards the laser. In other words the laser is not properly impedance matched to the interferometer. The impedance matching can be improved by placing another mirror of carefully chosen transmission - a power recycling mirror - between the laser and the interferometer so that a resonant cavity is formed between this mirror and the rest of the interferometer and no light comes back towards the laser [25]. There is then a power build up inside the interferometer, a build up which can be high enough to create the required kilowatt of laser light at the beamsplitter from ~ 10W or so out of the laser. This level of laser power is currently achievable from large single frequency Nd:YAG systems [26,27,28]. To enhance the sensitivity of the detector further and to allow some narrowing of the detection bandwidth, which may be valuable in searches for continuous wave sources of gravitational radiation, another technique known as signal recycling can be implemented [29,30,31]. This relies on the fact that sidebands created on the light by gravitational wave signals interacting with the arms do not interfere destructively and so do appear at the output of the interferometer. If a mirror of suitably chosen reflectivity is put at the output of the system as shown in Fig 4, then the sidebands can be recycled back into the interferometer where they resonate and hence the signal size over a given bandwidth (set by the mirror reflectivity) is enhanced.

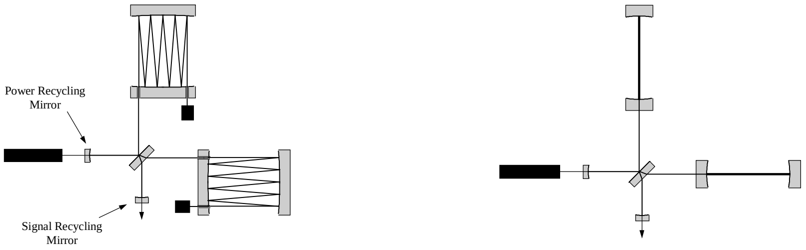

Fig.4. The implementation of power and signal recycling on the interferometers in the previous figure.

2.4 Long Baseline Detectors under Construction

Prototype detectors using laser interferometry have been constructed by various research groups around the world - at the Max-Planck-Institut für Quantenoptik in Garching [32], at the University of Glasgow [33], at California Institute of Technology [34], at the Massachusets Institute of Technology [35], at the Institute of Space and Astronautical Science in Tokyo [36] and at the astronomical observatory in Tokyo [37]. These detectors have arm lengths varying from 10m to 100m and have or had either multibeam delay lines or resonant Fabry-Perot cavities in their arms. Several years ago the sensitivities of some of these detectors reached a level - better than 10^{-18} for millisecond pulses - where it was sensible to decide to build detectors of much longer baseline which should be capable of reaching the performance required to have a real possibility of detecting gravitational waves. It should be noted that in order to improve the confidence level of any detection and to obtain the location of the source a number of interferometers are required worldwide. Thus an international network of gravitational wave detectors is now under construction. The American LIGO project comprises the building of two detector systems with arms of 4km length, one in Hanford, Washington State, and one in Livingston, Louisiana. The vacuum system, laser and input optics and first suspension system for the detector in Hanford are now installed and the vacuum system is in place in Louisiana. The French/Italian VIRGO detector of 3km arm length at Cascina near Pisa is at the stage where the central buildings are close to completion and vacuum tanks to house the interferometry are being installed. It should be noted that this detector which uses five-stage multi-pendulum systems for the suspension of its test masses is specially designed to be able to operate down to approximately 10Hz. The TAMA 300 detector, which has arms of length 300m, is at a relatively advanced stage of construction at the Tokyo Astronomical Observatory. This detector is being built mainly underground; the vacuum system is complete and initial operation with light in the arms has started. All the systems mentioned above are designed to use resonant cavities in the arms of the detectors, use standard wire sling techniques for suspending the test masses, and are to be illuminated by infra-red light from a Nd:YAG laser.

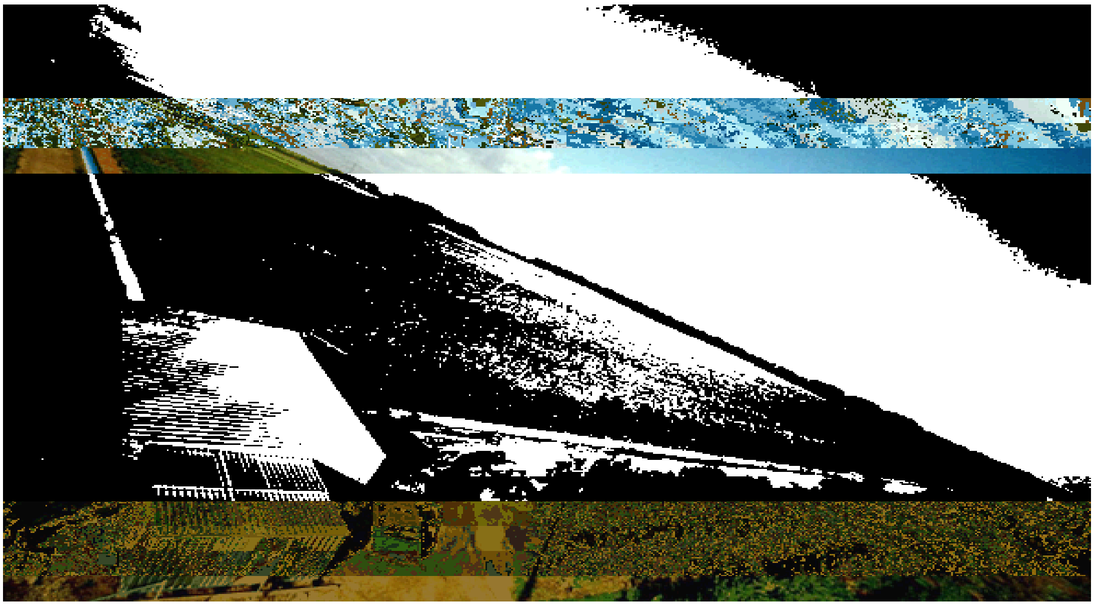

Fig. 5 A birds eye view of the GEO 600 detector, sited in Ruthe, near Hannover in Germany

The German/British project - GEO 600 - for a 600m detector near Hanover is somewhat different. It makes use of a four pass delay line system with advanced optical signal enhancement techniques, utilises very low loss fused silica suspensions for the test masses, and should have a sensitivity at frequencies above a few hundred Hz comparable to the first phases of VIRGO and LIGO when they are in operation at the beginning of next century. Illumination is again to be by infra-red light, provided by a 10W single frequency YAG laser. Construction is advancing well with the necessary buildings and vacuum pipes for the arms being in place. Installation of the suspensions for the optical elements is now beginning. A birds-eye view of the site showing the central building and the directions of the two arms is shown in Fig. 5.

This detector is based on the fundamental research carried out over many years at the Max-Planck-Institut für Quantenoptik, Garching, the University of Glasgow, the University of Wales, Cardiff, and more recently the University of Hanover and the Albert Einstein Institut, Potsdam. In two years time initial operation of the detector is expected to commence and during the following years we can expect some very interesting coincidence searches for gravitational waves, at a sensitivity level of approximately 10^{-21} for pulses of several milliseconds duration.

2.5 Longer Baseline Detectors in Space

Searches for gravitational wave sources at low frequency have been underway for a number of years using their possible effect on the phase of the radio signals from the millisecond pulsars PSR 1937+21 and PSR 1855+09 [38] and their possible effect on the Doppler shift of radar signals transponded back from space craft such as Ulysses [39]. The former experiment, sensitive to signals of frequency of the order of one cycle per year and lower, has been used to set a limit on the gravitational wave background in this frequency regime corresponding to an energy density per logarithmic frequency interval of less than 6×10^{-8} of the closure density of the Universe. The latter experiments have searched for continuous wave signals in the mHz region and have set a limit of approximately 3×10^{-15} for such signals. However perhaps the most interesting sources of gravitational waves - those resulting from black hole formation and coalescence - lie in the region of 10^{-4} Hz to 10^{-1}Hz and a detector whose strain sensitivity is approximately 10^{-23} over relevant timescales is required to search for these. The most promising way of looking for such signals is to fly a laser interferometer in space i.e. to launch a number of drag free space craft into orbit and to compare the distances between test masses in these craft along arms making significant angles with each other using laser interferometry. Two such experiments have been proposed. The first, LISA [8] is being proposed by an American/European team; it consists of an array of 3 drag free spacecraft at the vertices of an equilateral triangle of length of side 5×10^{6}km, and this cluster is placed in an Earth-like orbit at a distance of 1 AU from the Sun, and 20 degrees behind the Earth. Proof masses inside the spacecraft (two in each spacecraft) form the end points of three separate but not independent interferometers. Each single two-arm Michelson type interferometer is formed from a vertex (actually consisting of the proof masses in a 'central' spacecraft), and the masses in two remote spacecraft as indicated in Fig. 6.

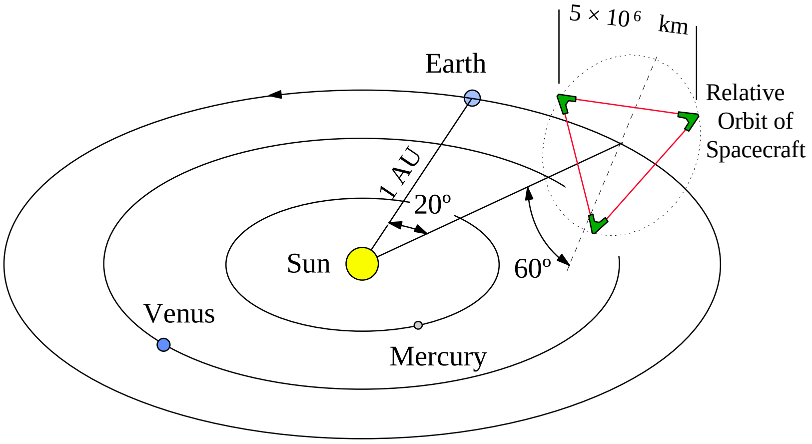

Fig.6 The proposed LISA detector

The three-interferometer configuration provides redundancy against component failure, gives better detection probability, and allows the determination of polarisation of the incoming radiation. The spacecraft in which they are accommodated shields each pair of proof masses from external disturbances (e.g. solar radiation pressure). Drag free control servos enable the spacecraft to follow the proof masses to a high level of precision, the drag compensation being effected using proportional electric thrusters. Illumination of the interferometers is by highly stabilised laser light from Nd:YAG lasers at a wavelength of 1.064 microns. For each interferometer - consisting of a central spacecraft and two distant spacecraft - the two lasers in the central spacecraft are phase locked together so they effectively behave as a single laser. The lasers in the end spacecraft are phase locked to the incoming light, and thus act as amplifying mirrors.

LISA, in a slightly earlier form with six spacecraft, two at each vertex, was adopted by ESA as a Cornerstone project in their post Horizon 2000 programme. However the timescale of this programme is somewhat long and following suggestions from the LISA Team group at JILA the lower cost three spacecraft version has recently been studied at JPL and could allow the possibility of an earlier launch as a NASA led or ESA led collaborative medium scale mission.

The second experiment, OMEGA [40], calls for three craft to be placed in a geocentric orbit, the arm length in this case being 10^9m and this is currently being proposed to NASA as a MIDEX mission.

3. CONCLUSION

A large amount of effort worldwide is now being invested in the development of both ground and spaced based searches for gravitational radiation and we are entering a new era where the signals from neutron star and black hole interactions will widen our understanding of the Universe. Beyond this, however, there is the very exciting prospect that gravitational wave astronomy will be like radio astronomy and X-ray astronomy and will allow the discovery of very active sources currently unknown to us.

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REFERENCES

[1] B.C. Barish, “LIGO: Status and Prospects” Proc. of Conference on Gravitational Wave Detection, Tokyo, Eds. K. Tsubono, M.K. Fujimoto, K. Kuroda, Universal Academy Press Inc, Tokyo (1997) 163-173

[2] J.-Y. Vinet et al, Proc. of Gravitation and Cosmology, ICGC-95 Conference, Pune, India 13-19 Dec 1995 Astrophysics and Space Science Library, Kluwer Academic Publishers 211 (1997) 89-93

[3] J. Hough et al “GEO 600: Current status and some aspects of the design” Proc. of Conference on Gravitational Wave Detection, Tokyo, Eds. K. Tsubono, M.K. Fujimoto, K. Kuroda, Universal Academy Press Inc, Tokyo (1997) 175-182

[4] K. Tsubono and the TAMA collaboration, “TAMA project” Proc. of Conference on Gravitational Wave Detection, Tokyo, Eds. K. Tsubono, M.K. Fujimoto, K. Kuroda, Universal Academy Press Inc, Tokyo (1997) 183-191

[5] C.M. Will, “Theory and experiment in gravitational physics” Revised edition, Cambridge University Press, Cambridge (1983)

[6] R.A. Hulse Rev. Mod. Phys. 66 (1994) 699

[7] J.H. Taylor Rev. Mod. Phys. 66 (1994) 711.

[8] "First International LISA Symposium", Classical and Quantum Gravity 14, 6, (1997); "Gravitational Waves, Sources and Detectors", Edoardo Amaldi Foundation Series Volume 2, Ed. I. Ciufolini and F. Fidecaro, World Scientific, (1997)

[9] B.F. Schutz, "Determining the nature of the Hubble constant" Nature 323 (1986) 310

[10] K. Danzmann et al, "LISA: Laser Interferometer Space Antenna for Gravitational Wave Measurements" Class. Quant. Grav. 13 11A (1996) A247-50

[11] R.L. Forward, D. Zipoy, J. Weber, S. Smith, H. Benioff, 189 Nature 473 (1961)

[12] J. Weber, Phys. Rev. Lett. 22 (1969) 1320

[13] J. Weber, Phys. Rev. Lett 25 (1970) 180

[14] P. Astone, M. Bassan, P. Bonifazi, P. Carelli, E. Coccia, C. Cosmelli, V. Fafone, S. Frasca, A. Marini, G. Mazzitelli, Y. Minenkov, I. Modena, G. Modestino, A. Moleti, G.V. Palletino, M.A. Papa, G. Pizzella, P. Rapagnani, F. Ricci, F. Ronga, R. Terenzi, M. Visco, L. Votano, International Conference on Low Temperature Physics, Prague, Czech Republic 8-14 Aug 1996, Czech. J. Phys. 46 suppl. pt S5 (1996) 2907-8

[15] E. Amaldi, O. Aguiar, M. Bassan, P. Bonifazi, P. Carelli, M.G. Castellano, G. Cavallari, E. Coccia, C. Cosmelli, W.M. Fairbank, S. Frasca, V. Foglietti, R. Habel, W.O. Hamilton, J. Henderson, W. Johnson, K.R. Lane, A.G. Mann, M.S. McAshan, P.F. Michelson, I. Modena, G.V. Palletino, G. Pizzella, J.C. Price, R. Rapagnani, F. Ricci, N. Solomonson, T.R. Stevenson, R.C. Taber, B.-X. Xu, "First gravity wave coincident experiment between resonant cryogenic detectors: Louisiana-Rome-Stanford" Astron. and Astro. 216 1-2 (1989) 325-32

[16] I.S. Heng, D.G. Blair, E.N. Ivanov, M.E. Tobar "Long term operation of a niobium resonant bar gravitational wave antenna" Phys. Lett. A 218 3-6 (1996) 190-6

[17] R.E. Spero in "Science Underground" ed. M.M. Nieto et al. AIP New York, (1983)

[18] P.R. Saulson, "Terrestrial gravitational noise on a gravitational wave antenna" Phys. Rev. D 30 (1984) 732

[19] P.R. Saulson, "Thermal noise in mechanical experiments" Phys. Rev. D 42 (1990) 2437-2445

[20] S. Rowan, S.M. Twyford and J. Hough, "The design of low loss suspensions for advanced gravitational wave detectors" Proc. 2nd E. Amaldi conf. on gravitational waves, CERN, Geneva July (1996) In press

[21] V. B. Braginsky, V.P. Mitrofanov, K.V. Tokmakov, "Energy dissipation in the pendulum mode of the test mass suspension of a gravitational wave antenna" Phys. Lett. A 218 (1996) 164-166

[22] S. Rowan, S.M. Twyford, R. Hutchins, J. Kovalik, J.E. Logan, A.C. McLaren, N.A. Robertson, J. Hough, "Q factor measurements on prototype fused quartz pendulum suspensions for use in gravitational wave detectors" Phys. Lett. A 233 (1997) 303-308

[23] L. Ju, M. Notcutt, D. Blair, F. Bondu, C.N. Zhao, “Sapphire beamsplitters and test masses for advanced laser interferometric gravitational wave detectors” Phys. Lett. A 218 3-6 (1996) 197-206

[24] W.A. Edelstein, J. Hough, J.R. Pugh, W. Martin, “Limits to the measurement of displacement in an interferometric gravitational radiation detector” J. Phys. E (Scientific Instruments) 11 7 (1978) 710

[25] R.W.P. Drever, J. Hough, A.J. Munley, S.-A. Lee, R. Spero, S.E. Whitcomb, H. Ward, G.M. Ford, M. Hereld, N.A. Robertson, I. Kerr, J.R. Pugh, G.P. Newton, B. Meers, E.D. Brooks III, Y. Gursel, in “Quantum optics, experimental gravitation and measurement theory” Eds. P. Meystre, M.O. Scully, Plenum Press, New York, (1983) 503-514

[26] O. Cregut, C.N. Man, D. Shoemaker, A. Brillet, A. Menhert, P. Peuser, N.P. Schmitt, P. Zeller, K. Wallermoth, “18W single-frequency operation of an injection-locked, CW, Nd:YAG laser, Phys. Lett. A 140 6 (1989) 294-8

[27] D. Golla, I. Freitag, H. Zellmer, W. Schone, I. Kropke, H. Welling, “15W single-frequency operation of a CW diode laser-pumped Nd:YAG ring laser” Opt. Comm. 98 1-3 (1993) 86-90

[28] R.J. Shine Jr., A.J. Alfrey, R.L. Byer, “40W TEM$_{00}$-mode, diode-laser-pumped Nd:YAG miniature-slab laser”, Opt. Lett. 20 5 (1995) 459-61

[29] B.J. Meers, “Recycling in laser-interferometric gravitational-wave detectors” Phys. Rev. D, (Particles and Fields) 38 8 (1988) 2317-26

[30] K.A. Strain, B.J. Meers, “Experimental demonstration of dual recycling for interferometric gravitational-wave detectors” Phys. Rev. Lett. 66 11 (1991) 1391-4

[31] G. Heinzel, K.A. Strain, J. Mizuno, K.D. Skeldon, B. Willke, W. Winkler, R. Schilling, K. Danzmann, “An experimental demonstration of dual recycling on a suspended interferometer” Phys. Rev. Lett. (1998) In press.

[32] D. Shoemaker, R. Schilling, L. Schnupp, W. Winkler, K. Maischberger, A. Rüdiger, “Noise behaviour of the Garching 30-meter prototype gravitational-wave detector” Phys. Rev. D (Particles and Fields) 38 2 (1988) 423-32

[33] D. Robertson, E. Morrison, J. Hough, S. Killbourn, B.J. Meers, G.P. Newton, K.A. Strain, H. Ward, “The Glasgow 10m prototype laser interferometric gravitational wave detector” Rev. Sci. Instr. 66 9 (1995) 4447-52

[34] A. Abramovici, W. Althouse, J. Camp, D. Durance, J.A. Giaime, A. Gillespie, S. Kawamura, A. Kuhnert, T. Lyons, F.J. Raab, R.L. Savage, Jr., D. Shoemaker, L. Sievers, R. Spero, R. Vogt, R. Weiss, S. Whitcomb, M. Zucker, “Improved sensitivity in a gravitational wave interferometer and implications for LIGO” Phys. Lett. A, 218 3-6 (1996) 157-63

[35] P. Fritschel, G. Gonzalez, B. Lantz, P. Saha, M. Zucker, “High power interferometric phase measurement” Phys. Rev. Lett. 80 15 (1998) 3181-4

[36] A. Araya, N. Mio, K. Tsubono, K. Suehiro, S. Telada, M. Ohashi, M.-K. Fujimoto, “Optical mode cleaner with suspended mirrors” Appl. Opt. 36 7 (1997) 1446-53

[37] E. Mizuno, N. Kawashima, S. Miyoke, E.G. Heflin, K. Wada, W. Naito, S. Nagano, K. Arakawa, “Effort of stable operation by noise reduction of 100m DL laser interferometer [TENKO-100] for gravitational wave detection” Proc. VIRGO 96, Cascina, World Scientific (1996) 108-110

[38] V.M. Kaspi, J.H. Taylor, M. Ryba, “High precision timing of millisecond pulsars. III. Long-term monitoring of PSRs B1885+09 and B1937+21” Astr. J. 248 2 pt.1 (1994) 712-28

[39] B. Bertotti, R. Ambrosini, J.W. Armstrong, S.W. Asmar, G. Comoretto, G. Giampieri, L. Iess, Y. Koyama, A. Messeri, A. Vecchio, H.D. Wahlquist, “Search for gravitational wave trains with the spacecraft ULYSSES” Astron. and Astro. 296 1 (1995) 13-25

[40] R.W. Hellings, “Gravitational wave detectors in space” Cont. Phys. 37 6 (1996) 457-69