FINAL REPORT ON NASA GRANT NAG5-4095:

PI: Peter L. Bender
JILA, UCB440
University of Colorado
Boulder, CO 80309

17 September, 2002

FINAL REPORT FOR GRANT PERIOD 1 JANUARY 1997 - 31 MARCH 1999:

EVENT RATE FOR LISA GRAVITATIONAL WAVE SIGNALS FROM
BLACK HOLE-MASSIVE BLACK HOLE COALESCENCES

Earlier work under a previous grant had been mainly on investigating the event rate for coalescences of white dwarfs or neutron stars with massive black holes (MBHs) in galactic nuclei [1]. Under the new grant, two studies were undertaken. One was an approximate extension of the earlier study to stellar mass black holes as the lighter object, with masses in the range of roughly 3 to 20 M_sun, rather than about 1 M_sun. The other was an improved estimate of the confusion noise due to galactic binaries against which the signals from BH-MBH coalescences would have to be detected.

In the earlier work, the mass of the white dwarfs (WDs) and neutron stars (NSs) was assumed to be about the same as that of the unevolved stars in the density cusp around the galactic center MBH. However, with the BH mass being substantially larger, the sinking down of BHs toward the center (mass segregation) became important, and was included in the model. A single representative mass of 7 M_sun was used.

The other main difference involved what happened after the compact object got scattered in close enough to the MBH to start losing appreciable energy and angular momentum by gravitational radiation. For WDs or NSs, it had been found [1] in most cases that the object would be perturbed considerably by other stars in the cusp before much energy had been lost. Thus the angular momentum would either increase enough so that the gravitational radiation

would be cut off, or would decrease enough so that the WD or NS would plunge into the MBH in just a few revolutions. The latter event would mean that the signal-to-noise ratio would not have time to build up, and the event would not be detectable. The ratio of gradual energy loss events to plunges was found to be roughly one to a few percent, and thus substantially decreased the expected rate of detectable events.

For BHs instead of WDs or NSs, the ratio of gradual energy loss events to plunges was found to be considerably larger, so that only a factor 2 or 3 was lost in the event rate. In both cases, the ratio was calculated by means of a Monte Carlo random walk in both energy and angular momentum, with drift because of the gravitational radiation. Expected signal strengths and frequencies were then calculated for a crude model involving a distribution of MBH masses and 0.1% of the stars in the cusp being BHs. The results were calculated for factor 2 ranges in MBH mass (from 0.25 to $4 \times M\_5$, where $M\_6 = 10^6 \ M\_sun$) and in redshift z. The range of redshifts with expected observable signals for 1 year of observations with LISA were found to be roughly as follows: z near 2 for $0.25 \times M\_6$; z = 1/2 to 2 for $0.5 \times M\_6$; z = 1/8 to 1 for $1 \times M\_6$; and z = 1/16 to 1/4 for $2 \times M\_6$. The lower cutoff in z for the higher MBH masses is because of the higher confusion noise and instrumental noise at the lower signal frequencies.

About the same time as the above results were being obtained, a paper by Sigurdsson and Rees [2] concerning the coalescence of compact objects with MBHs was published. The results were also encouraging, but the basis for the calculations was quite different. For example, only a random walk in energy was considered in investigating the ratio of gradual energy loss events to plunges. And the galaxy models used were characteristic of spirals, rather than M32, which was the model type of galaxy used in the JILA studies. Other related papers by Miralda-Escuda and Gould [3] and by Freitag [4] have since appeared, with only the random walk in energy included, and with other differences in the models used. It unfortunately has not yet been possible to extend the JILA studies to the types of models used in the other studies, in order to compare the results in more detail.

During the course of the work, it became clear that some additional studies were needed on the confusion noise due to galactic binaries. The noise due to conventional WD-WD binaries had been looked at carefully, but another type of binary had been suggested recently as being a concern also. This is AM CVn type binaries, which also are called helium cataclysmics or interacting WD binaries, where a low mass He star or a semi-degenerate He star is spilling mass over onto a carbon-oxygen WD primary. Because of the mass transfer, the semi-major axis may decrease for a while, and then increase again as the secondary loses most of its mass. Because of their very long lifetimes, it appeared that the space density of such systems might be fairly high.

The results of these additional confusion noise studies were published in papers by Hils [5] and by Hils and Bender [6]. Results were obtained under two different scenarios for how such binaries are formed. In one case the secondary initially is a low mass non-degenerate helium star, and in the second it is a semi-degenerate helium star. Both cases can be described as helium cataclysmics, in analogy with ordinary cataclysmic variables that have hydrogen rich secondaries.

The second scenario is somewhat preferred, but it still is possible that the real progenitors follow neither scenario. However, it appears better to include the effects on the gravitational wave confusion noise with the second scenario rather than to make no allowance for such binaries. The resulting confusion noise curve fortunately is not made much worse by including the estimated contribution from helium cataclysmics, and is being used in further

work.

FINAL REPORT FOR GRANT PERIOD: 1 APRIL 1999 - 31 MARCH 2002

SEPARATION OF LISA GALACTIC AND EXTRAGALACTIC SIGNALS

Work on this grant under a new proposal and new title shifted to
investigating different approaches to solving for individual WD-WD binary
signals from simulated data. The average number lambda of binary signals per
cycle/year frequency bin will decrease as the eight-thirds power of the
frequency, and, for 1 year of data, is expected to drop to about 0.2 near
3 mHz. The question investigated was how low lambda needs to be in order
that individual binary signals can be solved for and subtracted out from the
data, and how much information about interesting extragalactic signals will
be lost as a function of lambda because of having to do this.

The proceedure used started with simulated galactic binary data near 3 mHz.
It was assumed that, in processing a one year record of real data, the
signals from each 200 cy/yr band near 3 mHz would be heterodyned down to the
100 to 300 cy/yr band in order to reduce the number of time points needed in
the calculations (see [7]). The signals from sources having their barycenter
frame frequencies in roughly the central 70% of the interval would be treated
as having been determined to a first approximation accuracy level, and
subtracted out from the data. However, signals with barycenter frequencies
near the edges of the bands would be unreliable because of edge effects.
Thus the residuals would then be processed again with the boundaries of the
original 200 cy/yr bands shifted over so that they came at the centers of the
new bands. After this second set of signal searches is completed, a fairly
good first approximation to all the signals in a wider frequency band should
have been produced, and can be removed from the original data. A second
round consisting of least squares improvements to the parameters of the
signal sources can be carried out if desired.

The first test data sets generated consisted of 3 to 5 sources distributed
over a 30 to 50 cy/yr band. The formulas from Cutler [8] were used to
generate both the signals for the test data sets and templates for fitting
the data. The sources were assumed to be in the galactic plane, since this
is a good approximation for all but less than 1% of the sources which are
closest to the Sun and give the strongest signals. One caution is that only
sources with their angular momentum vector L pointing above or below the
galactic plane should be included, since reflecting L in the galactic plane
gives gravitational wave signals that are indistinguishable. The handling of
the Doppler shifts in the data was simplified because the phase shifts are
essentially identical across a 200 cy/yr frequency band for a given direction
to the source.

Some simplifications were made in generating the test data sets to keep the
problem as simple as possible. The main search approach used was a
sequential one, where a grid of templates covering the parameter space was
generated and cross-correlated with the data set to determine the signal
parameters giving the highest correlation. This signal was subtracted from
the data, and searches for the second, third, etc., most highly correlated
signals were made. At the end of this proceedure, one signal at a time was
put back, and the new residual set searched for improved values of the
parameters for each signal.

The above sequential approach was found to work in some cases. However, in
other cases the sets of parameters found improved only very slowly with
successive iterations. This is because errors in the parameters found the
first time through tend to be locked in through the induced errors in each of

the signals that are not being fit at any particular time.

Efforts were then concentrated on trying to understand better the difficulties in the search problem that persist even if single sources are searched for. It was found that correlations between some of the parameters are quite strong, and searches using steepest decent or conjugate gradient approaches rapidly find correlated parameter sets that give small residuals. But they have difficulty in finding the only slightly lower residuals corresponding to the true minima in the residuals. The directions to the sources and the frequencies are generally quite well determined, but the direction of L and the phase of the signal are considerably harder to find.

The experience with the search process during the first half of 2000 was reported by R. T. Stebbins during the Third International LISA Symposium at the Albert Einstein Institute in Golm, Germany on July 11-14, 2000. However, progress later in the year was slowed down considerably by illness of the Co-Investigator who was carrying out most of the studies, Dieter Hils. Because of illness, he was forced to go on sick and annual leave full time starting September 1, and in 2001 qualified for disability retirement.

In view of the above situation, some of the effort on the grant later in the year was diverted to following up on a suggestion made by Craig Hogan from the University of Washington at the 3rd LISA Symposium. Massimo Tinto from JPL presented a talk describing the use of a possible LISA observable which we will call the "symmetrized Sagnac observable" to help in separating instrumental noise from the strong confusion noise which limits the LISA sensitivity at frequencies from roughly 0.2 to 3 mHz. This observable is sensitive to the instrumental noise, but at frequencies below about 20 mHz it is only weakly sensitive to gravitational waves. The talk by Tinto was based on earlier very important work by Armstrong, Estabrook and Tinto on an improved method called Time Delay Interferometry for analysing the LISA data to remove the effects of laser frequency noise.

Hogan suggested that a somewhat different approach might make it possible to determine the frequency-smoothed level of an isotropic gravitational wave background, even if that level was below the instrumental noise level. This method was investigated in detail by Hogan and Bender during the next year, and appears to work well. Talks on the analysis method were given by Hogan at the Texas Symposium on Relativistic Astrophysics in Austin in December, 2000 and at the Gravitational Wave Data Analysis Workshop in Trento, Italy, in December, 2001, and by Bender at the AAS meeting in San Diego in January, 2001, at the Winter Conference on Gravitational Waves in Aspen in February, 2001, and at the APS meeting in Washington in April, 2001. A paper on the method [9], "Estimating stochastic gravitational wave backgrounds with the Sagnac calibration", by Hogan and Bender, was published in Phys. Rev. D in September, 2001.

The main conclusion of the Sagnac Calibration work is that the gravitational wave background near 10 mHz due to all the extragalactic close white dwarf binaries in the universe can be detected by LISA, if present estimates of the formation rate of such binaries at substantial redshifts are roughly right. The resulting sensitivity for setting limits on a possible primordial gravitational wave background generated long before the cosmic microwave background also was considered briefly, both for LISA and for a possible LISA follow-on mission.

It is expected that the ultimate limits on detecting a primordial background will be set almost entirely by astrophysical backgrounds generated much later, except possibly above 0.1 Hz if extremely optimistic assumptions about future improvements in instrumental sensitivity are made. Some possible scenarios for generating detectable primordial backgrounds exist, but they

are regarded as very unlikely, unless the generation of baryons turns out to be associated with an electroweak phase transition in the early universe or some even more exotic mechanism connected with brane worlds is found.

An associated activity was participating, with Scott Hughes from the Institute for Theoretical Physics in Santa Barbara and Craig Hogan, in a Workshop on the Future of Particle Physics in Snowmass in July, 2001. We represented what the LISA mission and possible follow-on missions could do in a Working Group on Astro/Cosmo/Particle Physics. This led to a paper, "New physics and astronomy with the new gravitational-wave observatories", by Hughes, Marka, Bender, and Hogan [10], that was included in the (electronic) proceedings of the Workshop.

Starting in September 2001, work on the original objective of studying the limitations for extragalactic sources from galactic binaries was resumed. A first year graduate student in the Department of Physics, Wendy Wilson, began converting and writing codes to generate test cases of signals and to fit out all the individual sources that could be identified in the data. The conversion of codes and writing of new codes was undertaken because the older codes were for an obsolescent VAX type operating system, and a switch was made to the now much more widely used UNIX system.

As earlier, the process being followed is to generate simulated data representing gravitational waves reaching the solar system barycenter in a frequency band roughly 200 cycles/year wide near 3 mHz. This includes signals from up to about 30 galactic binaries, realistically distributed in direction and distance. Since the translational and rotational motion of the LISA spacecraft configuration during a year turns a monochromatic galactic binary signal near 3 mHz into a reduced amplitude central frequency plus about 30 significant sidebands, the analysis is actually carried out for the 200 cy/yr band to avoid losing some of the sidebands. It is expected that the results will give a good approximation to how well the galactic sources can be fit out from the data for frequencies in the central 100 to 150 cy/yr of the frequency band analysed.

A frequency band near 3 mHz was chosen for the initial work because a substantial fraction of the information in the data about extragalactic sources is expected to remain after fitting out the galactic binaries at frequencies higher than this. The end product expected from this research is an evaluation of how much information about important extragalactic sources is lost as a function of frequency because of having to fit out the galactic binaries. The results will be of particular importance for fairly weak extragalactic sources such as intermediate mass black hole binaries at substantial redshifts or highly unequal mass black hole binaries. Such sources sweep sufficiently rapidly in frequency so that statistical information on how much information will be lost as a function of frequency will be all that is needed. The work is being continued under another grant.

References:

[1] D. Hils and P. L. Bender, "Gradual Approach to Coalescence for Compact Stars Orbiting Massive Black Holes", Ap. J. 445, L7-L10 (1995)

[2] S. Sigurdsson and M. J. Rees, "Capture of stellar mass compact objects by massive black holes in galactic cusps", Mon. Not. R. Astron. Soc. 284, 318-326 (1997)

[3] J. Miralda-Escude and A. Gould, "A Cluster of Black Holes at the Galactic Center", Ap. J. 545, 847-853 (2000)

[4] M. Freitag, Monte Carlo cluster simulations to determine the rate of compact star inspiralling to a central galactic black hole", Class. Quantum Grav. 18, 4033-4038 (2001)

[5] D. Hils, "Confusion Noise Estimate for Gravitational Wave Measurements in Space", in LASER INTERFEROMETER SPACE ANTENNA, Proc. 2nd Int. LISA Symp. on the Detection and Observation of Gravitational Waves in Space, Amer. Inst. of Phys. Conf. Proceedings 456 (AIP, New York, 1998), pp. 68-78

[6] D. Hils and P. L. Bender, "Gravitational Radiation from Helium Cataclysmics", Ap. J. 537, 334-341 (2000)

[7] B. F. Schutz, in The Detection of Gravitational Waves, ed D. G. Blair (Cambridge University Press, Cambridge, 1991), pp. 406-452

[8] C. Cutler, Phys. Rev. D 57, 7089-7102 (1998)

[9] C. J. Hogan and P. L. Bender, Phys. Rev. D, Vol. 64, 062002, 1-11 (2001)

[10] S. A. Hughes, S. Marka, P. L. Bender and C. J. Hogan, Proc. Workshop on the Future of Particle Physics (electronic), Snowmass, CO (July, 2001)