PRESENT AND FUTURE OF RESONANT DETECTORS

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ABSTRACT

some elementary considerations on:

• BAR DETECTORS: WHY ?
• Bar Detectors: how do they work ?
• SENSITIVITY and BANDWIDTH: WHERE WE STAND and where can we go ?
  – Handles to improve present performances
• Some data from our detectors…
• New detectors for the future: MINIGRAIL and DUAL
RESONANT DETECTORS, WHY?

Bars with respect to Interferometers:

- Technology:
  different principles and instrumentation

- Complementary Frequency Band
  HF signals allow to study unique features of compact objects

- Symmetry properties
  discriminating the signal quadrupole character

- Detectors presently in reliable operation
Quasi-Periodic Oscillations

- NS and BH XRBs sometimes exhibit QPOs
- Frequencies are high (kHz QPOs), so the oscillations occur deep in the potential well
- Relativistic effects are likely to be important

From dr. Narayan’s talk
V. Ferrari et al. (2002)
RELIABLE OPERATION:
last 4 days of data in Explorer and Nautilus

Burst energy sensitivity:
1 mK = 85 neV
in a 2300 kg resonator!

Each data point in either plot is a
1 minute average of the data
filtered at ~200 Hz
RESONANT DETECTORS:

Yesterday: J. Weber

Tomorrow
The detectors of the Roma-Frascati group: 
**EXPLORER and NAUTILUS**

**Today**

Bar Al 5056  
M = 2270 kg  
L = 2.97 m  
Ø = 0.6 m  
$\nu_A = 915 \text{ Hz } @ \ T = 2.5 \text{ K}$  
Cosmic ray veto (recently completed)

$\nu_A = 935 \text{ Hz }$ (recently tuned)  
Al 5056 bar  
M = 2270 kg  
L = 2.92 m  
Ø = 0.6 m  
Cooled by a dilution fridge  
$T=130 \text{ mK}$  
Cosmic ray telescope veto
The GW excites the longitudinal mode of vibration of a massive (~2 ton) cylinder.

\[ h = \frac{\Delta L}{L} \]

\[ K(f) = \frac{S(f)e^{i2\pi f_0}}{N(f)} \]

**Mechanical vibration** → **Electrical signal** → **DATA** → **Matched Filtering**

- Seismic noise
- Thermal noise
- Electronics noise
- Cosmic ray noise

**Matched Filtering**

**Low and ultralow temperature**

**Low noise amplifier (SQUID)**

**Veto**

**Seismic noise**

**Mechanical filters**

**Low noise amplifier (SQUID)**

**Veto**
The readout of Explorer, Nautilus and Auriga

- small gap (10µm) capacitive pick up, d.c. biased with $E \sim 10^7$ V/m
- Superconducting matching transformer ($L_p = 2$ H, $L_s = 2$ µH)
- High sensitivity d.c. SQUID (JJ technology) $\phi_{\text{min}} = 2 \mu\phi_o / \sqrt{\text{Hz}}$
The rosette capacitive transducer; gap=9µm
Quantum at work

**dc-SQUID**

- Superconducting loop with inductance $L$
- 2 Josephson junctions: critical current $I_0$, shunt resistance $R$, capacitance $C$
- Input inductance $L_{in}$, coupling $\alpha$
$S_h(f) = \text{Spectrum of a g.w. excitation that would appear equal to the noise in the antenna (SNR=1)}$

The bandwidth depends on the transducer ($\beta$) and amplifier ($T_n$).

The peak sensitivity depends on $T/MQ$.

We need to broaden AND deepen the dips in this curve:

$\Rightarrow$ More peak sensitivity

$\Rightarrow$ AND more bandwidth
EXPLORER has been on the air since May 2000 with:
- new, 10 µm gap transducer
- New, high coupling SQUID

The noise temperature is < 3 mK for 84% of the time.

Bandwidth: the detector has a sensitivity better than $10^{-20}$ Hz$^{-1/2}$ on a band larger than 40 Hz.
REAL DATA, A QUICK REVIEW

- Search for relic background of g.w.
- Search for periodic sources (and SN1987a remnant)
- Search for burst:
  - The IGEC upper limit
  - 2001 data from Explorer and Nautilus
- Detection of cosmic rays in Nautilus
• Crosscorrelation of EXPLORER and NAUTILUS data

12 hours of data

$\Delta f = 0.1 \text{ Hz}$

$S_{12} < 1 \times 10^{-44} \text{ Hz}^{-1}$

$\Omega_{GW}(920.2) < 60$

\[
S_{12}(f; \Delta f) = \frac{1}{\Delta f} \int_{f-\Delta f/2}^{f+\Delta f/2} H_{1h}(f')H_{2h}^*(f')df'
\]

\[
\Omega_{gw}(f) = \frac{S_h(f)f^34\pi^2}{3H_0^2}
\]

“Crosscorrelation measurement of stochastic gravitational waves with two resonant gravitational wave detectors”,
NEXT SEARCH, ON 2003 DATA:

- Will optimize overlapping bandwidth by acting on the bias E field
- Potential common band is ~ 30 Hz = 300 x that exploited in ’99.
• Limits of $\Omega_{gw} < 1$ achievable cross-correlating data from a bar-bar couple or from a bar-interferometer couple:

• The cross-correlation of 4 months of NAUTILUS and AURIGA data, at the sensitivity expected in the next run, would put the limit at $\Omega_{gw} \leq 0.1$

• Joint analyses with VIRGO, NAUTILUS and AURIGA may put limits at the level $\Omega_{gw} \leq 3-5 \times 10^{-3}$ (1y integration time, NAUTILUS upgraded and AURIGA phase 2, and VIRGO at $10^{-22} \text{ Hz}^{-1/2}$ @900 Hz)
The search for burst signals with a single detector is meaningless. It is almost impossible to distinguish the candidate events from the background of noise. The “coincidence analysis” between the event candidates of different detectors strongly decrease the false alarm probability.

\[ \lambda = N \left( \frac{\Delta t}{T_{\text{obs}}} \right)^{N-1} \prod_{i=1}^{N} n_i \]
What is an event?

- Energy threshold
- Time

Diagram: Energy vs. Time (NA 278)
• Collaboration for data exchange between the five resonant detector operating world wide
ALLEGRO  AURIGA  NIOBE

EXPLORER  NAUTILUS
Number 514 (Story 1), 29 November 2000 by Phillip F. Schewe and Ben Stein

New Upper Limit on Gravity Wave Events in Our Galaxy

The International Gravitational Event Collaboration (IGEC) is the first ever network of cryogenic resonant-cylinder gravity wave detectors. It consists of five widely spaced detectors: one in the US (Baton Rouge), two in Italy (Legnaro and Frascati), one in Switzerland (at CERN), and one in Australia (Perth).

Searching for passing gravity waves is a delicate art since it involves sensing deformations much smaller than the size of an atomic nucleus in huge detectors meters or kilometers in size. In the resonant detector approach this means watching for longitudinal vibrations in chilled automobile-sized metal cylinders. In the interferometer approach (used at LIGO; see, for example, Update 442) the deformation is the change in the separation of distant mirrors attached to test masses. Gravity waves strong enough to be detected will most likely come from events such as the coalescence of black holes or neutron stars, and these are rare. IGEC reports now that in its first operational period it has observed no gravity waves. From this they calculate an upper limit of the order of one per year in the rate at which such gravity wave events occur in our galaxy.

GEC is not only striving to have the sensitivity to record gravity waves from events out to distances of 100 million light years but is also hoping to be able to locate the source of the waves in the sky.
• Upper limit with 95% confidence on the amplitude of a single GW burst with optimum parameters

\[ 4 \times 10^{-3} \, M_\odot \text{ from GC} \]

\[ h = 4 \times 10^{-18} \]
EXPLORER-NAUTILUS EVENTS OF 2001

DATA-EVENT SELECTION:
• All events in coincidence within ±5 s with seismometer signals were vetoed (-8%)
• All events corresponding to hourly averaged $T_{\text{eff}}> 10$ mK and $T_{\text{eff}}> 7$mK in the 10 minutes before the event were eliminated
• Only events belonging to working periods with duration longer than 12 hours are considered

$=> 1490$ hrs of coinc. Operation

COINCIDENCE SELECTION:
• within a time coincidence (adaptive) $\sim 0.4$ s

$=> 43$ coincident events

• with event energies “compatible with a common cause” ($\pm 1\sigma$)

$=> 31$ coincident events
RESULTS OF THE ANALYSIS

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<tr>
<th>Sidereal time</th>
<th>Solar time</th>
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<td><img src="image1.png" alt="Graph" /></td>
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* = coincidences
______ = accidentals
Energy correlation (no energy filter)

- Events of the sidereal peak (hours 3-5) strongly correlated
- Probability for Gaussian distribution $<10^{-3}$

Fig. 8: Correlation between the event energies of NAUTILUS with those of EXPLORER for the eight coincidences occurred in the sidereal hour interval 3 to 5, in time periods $\geq 1$ hour. The correlation coefficient is 0.96. No energy filter was applied.
SEARCH FOR CONTINUOUS WAVES

- ALLEGRO put upper limits ($4 \times 10^{-23}$ over 1 Hz band) on signals from the GC and 47Tucanae using one month of data

- Limit for signals in the GC, using 95 days of EXPLORER data $h_c=3\times 10^{-24}$ (Astone et al. PRD 65, 022201, 2002)

- Overall sky search over 2 days of data is now running: limit at the level of $h_c=3\times 10^{-23}$ (1 million points, by choosing spin-down parameter and position randomly) (Astone, Borkowsky, Jaranowsky, Krolak, PRD, 65,042003, 2002)

- Collaboration with VIRGO-Rome group. Application of the strategy for the pulsar search to the EXPLORER and NAUTILUS data

$$SNR = \frac{h \cdot t_{obs}}{2 S_h(\nu)}$$
Evidence for a triaxial faint pulsar associated with SN1987a has been found in data taken from 5 detectors in the optical/near-infrared bands in the years 1992-1996 (Middleditch et al., New Astronomy, 5, 243, 2000).

\[ P = 2.14 \, ms; \]
\[ P \approx 2 \cdot 10^{-10} \, Hz/s; \]
\[ P_{\text{mod}} \approx 10^3 \, s \]

\[ \Rightarrow f_{GW} = 935.0 \, Hz \]
\[ \Rightarrow h_{\text{max}} \approx 4.7 \times 10^{-26} \]

- So, we chopped the bar of Nautilus to resonate @ 935 Hz
Bursts

Class. Quant. Grav. 18, 43 (2001)

Continuous signals


Stochastic Background


Search for correlation with GRB’s

Gravitational near field

Effect of cosmic rays
...Therefore, to improve sensitivity:

- **We need to improve the peak spectral sensitivity** $\tilde{h}(f_a)$
  - Increase $M$: large and/or multimode detectors
  - Reduce $T/Q$: ultracryogenics. New materials

- **We also need to increase the bandwidth** $\Delta f$
  - Increase $\beta$: transducer w/ tighter coupling
  - Reduce $T_n$: better amplifier (double SQUIDs)
IMPROVING $T_n$: Better Amplifiers

A SQUID is so good an amplifier that noise from the second stage is usually dominant.
The only suitable second stage is another d.c. SQUID.

However the two devices tend to disturb each other !!!

Several efforts underway to produce a reliable amplifier for antenna Readouts
IMPROVING T/Q: (I)

- New, powerful Dilution Refrigerators

- MINIGRAIL was cooled (Jan 2003) to 80 mK

- Cooling below 30 mK appears possible

- $T_{\text{min}}$ probably limited by ortho-para H conversion.
IMPROVING THE ANTENNA CROSS SECTION (II): SPHERES

• Need a larger mass (larger cross section, or lower thermal noise). This can be achieved with
  – One single huge resonator
  – Distributing the mass over many small detectors

• Besides, the resonator mass can be better exploited by monitoring all the modes that are sensitive to g.w.
  $\Rightarrow$ use the 5 quadrupole modes of a sphere.
Large cross section

\[ \sigma_n \propto M v^2 \]

- Due to larger mass \( \rightarrow 17 \times \)
- Due to omni-directionality \( \rightarrow 4 \times \)
- Total \( \rightarrow 70 \times \)
Exploiting the resonant-mass detector technique: the spherical detector

We might eventually have an array of small spherical resonators!

MINIGRAIL
Leiden (Netherlands)

MARIO SHENBERG
Sao Paulo (Brasil)

SFERA
Frascati (Italy)

CuAl(6%) sphere
Dia = 65 cm
Frequency = 3 kHz
Mass = 1 ton

TIGA, PRL 1993
Hollow sphere, PRD 1998
Dual sphere, PRL 2001
SPHERES AROUND THE WORLD
NEXT RUN OF AURIGA (fall 2003..)

- AURIGA II run UltraCryo
- AURIGA I run
- AURIGA II run Cryo

Graph shows:
- Frequency vs. $S_{\text{in}}^{1/2}$
- $10^{-22}$ to $10^{-21}$

Diagram highlights:
- LHe4 vessel
- Al2081 holder
- Electronic wiring support
- Compression Spring
- Transducer
- Sensitive bar
- Thermal Shield
distance measurement between two concentric bodies = h measurement
We apply the same detection principle to a toroidal detector. This geometry can be equipped with a capacitive or inductive transducer with SQUID read-out:

- Wide area transducers (not affected by the thermal noise produced by short-wavelength normal modes)
- Natural implementation of mode-selective detection

GWADW 2002 Workshop – Dual Resonant Mass Detectors
THE FUTURE (in the age of interferometers)

• There is still ample room for improvements in sensitivity
• LIGO preliminary data shows IFOs might take longer to operate than expected: bars are still the only sentinels
• A coincident detection by two totally different instruments will be a stronger evidence
• Cross correlation IFO-Bar for stoch. bkgnd will be crucial \( (D < \lambda/2\pi) \)
• New, upcoming multimode resonators will exploit the technology with a sensitivity boost + omnidirectionality