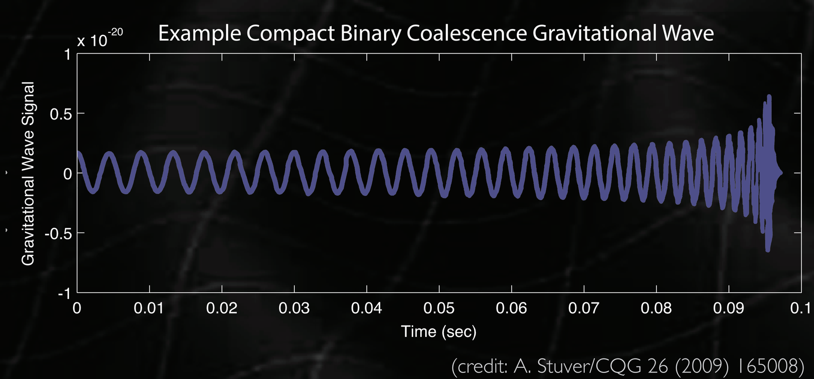
SOURCES OF GRAVITATIONAL WAVES

{EXTREME ASTROPHYSICAL OBJECTS}

Coalescing Compact Binaries

Compact binary systems consist of two extremely dense objects in orbit around one another. Ground-based gravitational-wave detectors are sensitive to gravitational waves from binaries made of neutron stars and/or stellar-mass black holes.

Compact binary systems undergo several evolutionary phases as they emit gravitational waves. In the early phase, energy loss from gravitational-wave emission causes the binary orbit to circularize and slowly shrink. This is called the inspiral phase. Eventually, the two objects reach the innermost stable circular orbit and plunge together in a fraction of a second to form a single black hole. This is called the merger phase. Finally, gravitational waves with a characteristic ringing frequency are emitted over a fraction of a second as the resulting black hole relaxes to its final form. This is called the ringdown phase.



(credit: A. Stuver/CQG 26 (2009) 165008)

The inspiral phase: Gravitational-wave signals produced in the inspiral phase can be accurately modeled using the post-Newtonian approximation to general relativity. In this phase, the frequency and amplitude of gravitational waves from coalescing binaries increase as the binary orbit shrinks. This produces a characteristic "chirp" signal, whose amplitude and frequency depend on a number of parameters such as the masses of the elements, geometry of the detector-source configuration, and the shape of the orbit. Gravitational-wave astronomers will measure these parameters by monitoring the frequency and amplitude of the waves in a worldwide network of detectors.

When gravitational-wave astronomy matures, signals from the inspiral phase will be used to perform high precision tests of general relativity, measure the Hubble constant, map out the spacetime geometry surrounding black holes and other objects, gain information on the equation of state of nuclear matter, and learn more about the formation and population of compact binaries in the universe.

The merger phase: Until recently, little has been known about the waves emitted during the merger of the binary elements. Advancements in numerical relativity in the past decade, however, are making it possible to solve the equations of general relativity for compact binary mergers. When the waves from merger events are detected, they may yield information about the internal structure of neutron stars, the equation of state of extremely dense nuclear matter, and the strong-field gravity near black hole event horizons.

The ringdown phase: If a spinning black hole is perturbed from its stable configuration during merger, it will oscillate with a collection of characteristic frequencies before eventually returning to a stable configuration. The oscillation properties of a black hole are surprisingly similar to those of a ringing bell. Just as a bell has a unique tone and timbre determined by its size and composition, each black hole rings with a unique fundamental pitch and duration that depends on its mass and rate of spin.

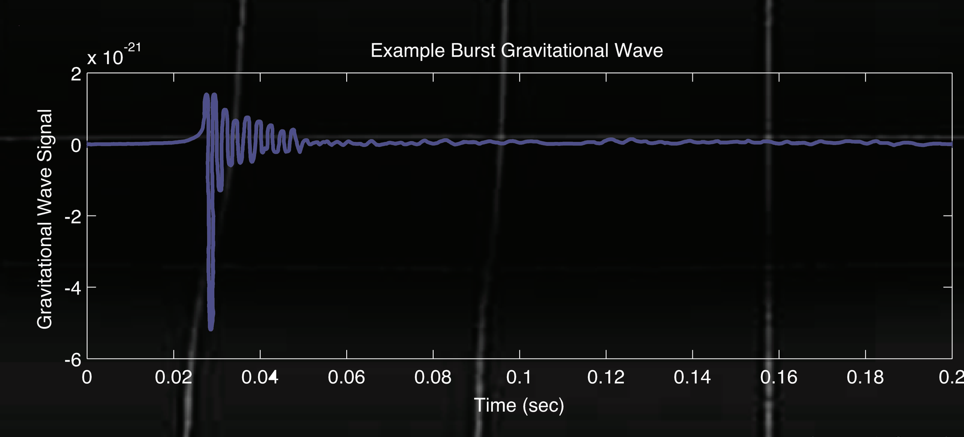
Other Burst Sources

Bursts of gravitational waves are signals that last for only a short period of time. Compact binary coalescence is anticipated to be a dominant source of gravitational wave bursts, but other objects are expected to produce bursts as well, so we must be prepared to detect a wide variety of possible signals. These include:

Core collapse supernova: When a star has exhausted its nuclear fuel, it collapses to form a neutron star or black hole. The collapse, bounce, and subsequent oscillation of the stellar core can produce gravitational waves.

Boiling of a newborn neutron star: The temperature of a newborn neutron star will be above 10^9 K. This extreme heat may lead to a convective instability in the neutron star, in which material from the core is dragged up to the neutrinosphere. The neutron star may boil like this for ~0.1 seconds, in which time ~30 gravitational wave cycles would be emitted. Since most of the neutron star material is in motion, these waves would have a characteristic amplitude $h_c \sim 10^{-21}$ at 30kpc.

Centrifugal hangup: If the pre-collapse core is rapidly spinning, it may "hang up" in a non-axisymmetric configuration during supernova collapse. This asymmetry is radiated away through gravitational waves.



(credit: A. Stuver)

Continuous Wave Sources

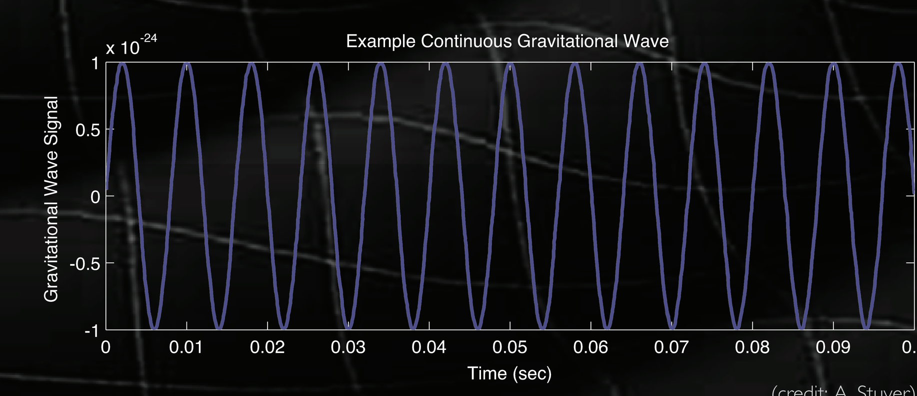
Non-axisymmetric rotating neutron stars are a potential source of continuous gravitational waves. Neutron stars are believed to be very nearly axisymmetric, but one could radiate gravitational waves for any of the following reasons:

Wobbling about rotation axis: If the rotation axis of the star is not aligned with a principal moment of inertia, the star will radiate waves with an amplitude proportional to $\theta_w \epsilon_p$, where θ_w is the wobble angle (assumed to be small), and ϵ_p is the poloidal ellipticity of the star.

Shear stress in the stellar crust: The neutron star crust is a Coulomb lattice which can support a sizeable ellipticity ϵ_e, where ϵ_e is the equatorial ellipticity. Theoretical estimates require ϵ_e to be less than 10^{-5} for normal neutron star models.

Accreting neutron stars: The spin frequencies of neutron stars in low-mass x-ray binaries are mysteriously low for systems that are accreting so much angular momentum. The emission of gravitational waves could explain the low spin frequency problem (that the observed spins are well below the centrifugal break-up value) if the accreting object has a large enough quadruple moment.

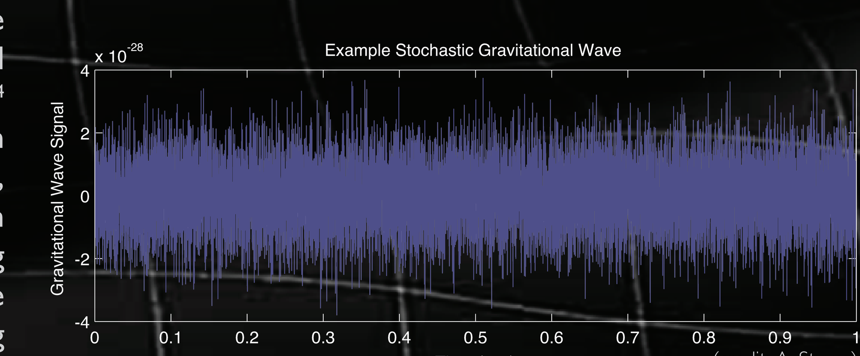
Unstable modes of neutron stars: Some oscillation modes of rotating neutron stars are unstable; that is, their amplitudes grow as they radiate gravitational waves. The fundamental modes have buoyancy as a restoring force and are confined to the surface of the star. Many other kinds of modes are possible too. Rossby modes are caused by the Coriolis force acting as a restoring force along the surface of the neutron star and are of significant interest because gravitational-wave emission always pushes them towards instability.



(credit: A. Stuver)

Stochastic Backgrounds

A stochastic background is a bath of gravitational radiation (somewhat analogous to the cosmic microwave background as a bath of electromagnetic radiation) created by a very large number of weak, independent, individually unresolvable sources in the sky. Processes in the early universe should have produced a stochastic background of gravitational waves with frequencies in the range 10^{-18} Hz — 10^4 Hz. Such a background would have decoupled from matter roughly 10^{-43} seconds after the Big Bang, much earlier than electromagnetic decoupling in the early universe (at about 10^5 years after the Big Bang). The detection of these waves would provide a unique probe of the very early universe, allowing us to look farther back in time than with conventional electromagnetic astronomy.

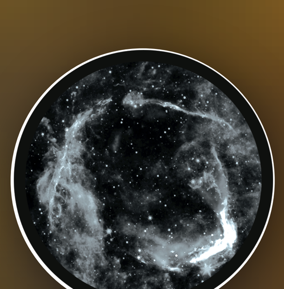


(credit: A. Stuver)

Other Exotic Sources

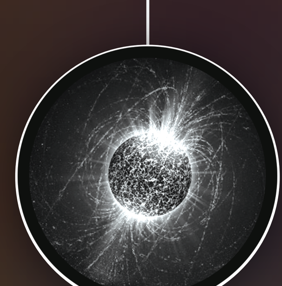
Gravitational-wave observatories will allow us to observe the universe in a completely new context. We expect to develop a better understanding of neutron stars, black holes, and the early universe. One of the most exciting prospects, however, is the detection of poorly modeled or even completely unexpected sources. The large number of theoretical sources of gravitational waves forms a vast zoo. Among these are boson stars, naked singularities with objects spiraling into them, primordial black holes, and cosmic strings. Even the most imaginative scientist may not have considered the objects that nature conspires to make the strongest source of gravitational waves in our universe. This is the promise of gravitational-wave astronomy, to bring us new and exciting observations to better understand the universe in which we live.

(background credit: NASA)



185

A "bright star" observed by ancient Chinese astronomers in 185 AD is considered the earliest recorded supernova. The image shows recent infrared images of the supernova remnant. (credit: NASA/JPL-Caltech/UCLA)



1933

Fritz Zwicky and Walter Baade predict the existence of neutron stars as a result of the supernova explosion of normal stars.
(credit: Casey Reed/Penn State University)

1967

Gamma-ray bursts are first detected by the Vela satellites, which were designed to detect covert nuclear weapons tests.
(credit: Dana Berry/NASA)

1968

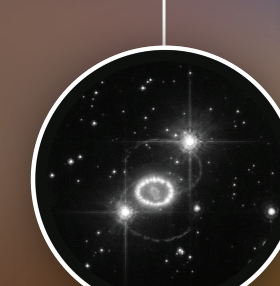
Thomas Gold proposes that pulsars are isolated, rotating neutron stars emitting electromagnetic radiation. (credit: Mysid/Roy Smits)

1974

Antony Hewish is awarded the Nobel prize in physics for the 1967 discovery of the first pulsar by Hewish and Jocelyn Bell.
(credit: Daily Herald Archive/Science & Society Picture Library)
(credit: Churchill College)

1978

Arno Penzias and Robert Woodrow Wilson are awarded the Nobel prize in physics for the 1964 discovery of the cosmic microwave background, which was crucial evidence for the Big Bang theory. (credit: NASA)



1987

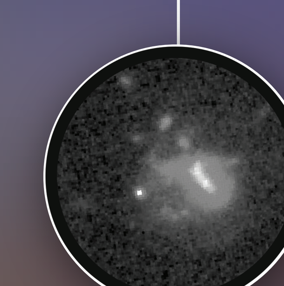
Supernova SN 1987A is one of the closest supernovae ever observed. If Advanced LIGO had been operational, it may have been able to detect gravitational waves from the explosion. (credit: ESA/Hubble & NASA)

1993

Joseph Taylor and Russell Hulse are awarded the Nobel prize in physics for the 1974 discovery of the first binary pulsar, which provides indirect evidence of gravitational-wave emission.
(credit (Taylor): Princeton University)

1999

The Chandra X-ray Observatory finds a X-ray point source at the center of the supernova remnant Cassiopeia A. This indicates the presence of a neutron star or black hole. If it is a young radio-quiet neutron star, its gravitational-wave emission could be detectable by Advanced LIGO.
(credit: HST/NASA/ESA)



2005

An afterglow for a short gamma-ray burst is observed, leading to the theory that short gamma-ray bursts arise from collisions between a black hole and a neutron star or between two neutron stars.
(credit: Derek Fox/Penn State University)

LIGO Scientific Collaboration

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