Neutron Stars, Pulsars, Millisecond Pulsars, and Gravitational Radiation:

A PRIMER

A neutron star is the collapsed core of a massive star left behind after a supernova explosion. The original massive star contained between 8 and 20 times the mass of our Sun, that is, 8-20 solar masses. (More massive stars collapse into black holes.) The remnant neutron star compresses at least 1.4 solar masses into a sphere only about 10 miles (16 kilometers) across.

This material is crushed together so tightly that gravity overcomes the repulsive force between negatively charged electrons and positively charged protons. The resulting structure of the star is complex, with a solid crystalline crust about half a mile (one kilometer) thick encasing a core of superfluid neutrons and superconducting protons. Above the crust exists both an ocean and atmosphere of much less dense material. Astronomers Walter Baade and Fritz Zwicky of the California Institute of Technology first predicted the existence of neutron stars in 1934, but they were not discovered until over 30 years later.

Pulsars are a special category of spinning neutron stars, discovered in 1967 by Jocelyn Bell, an astronomy graduate student working with Prof. Antony Hewish at Cambridge University in England. Pulsars derive their name from “pulsating radio sources” because they were first observed at radio wave frequencies. Hewish won the 1974 Nobel Prize in Physics along with Sir Martin Ryle for their “pioneering discoveries in radio astrophysics.” Hewish was cited for his “decisive role in the discovery of pulsars.”

From our earthly vantage point, pulsars appear to pulse with light with each rotation. Their light, like a lighthouse beam, sweeps across the Earth. Some pulsars emit visible light, X-rays, and even gamma-rays. All pulsars are neutron stars, but (so far as we know) not all neutron stars are pulsars, because not all neutron stars radiate light (such as radio waves or X-rays) with such steady pulses.

Pulsars are divided into two main categories, isolated pulsars and binary pulsars. Isolated pulsars (which include most radio pulsars) produce radiation primarily through their rotation, as they gradually slow down and cool off. Their light is generated by electrons caught in the pulsar’s strong magnetic field, concentrated and emitted near the magnetic poles. Thus, much of an isolated pulsar’s visible energy is funneled from the rotating magnetic pole region. The precise location of the beam is debated.

Binary pulsars are those in orbit with a companion star, most often hydrogen-burning stars like our Sun. Such a pulsar can pull over, or accrete, matter from its stellar companion as their orbits bring these objects in close contact with each other. The violent accretion process can heat the gas being transfer and produce X-ray light. The X-ray light from this matter, under the influence of magnetic fields, can also appear to pulsate at the pulsar’s rotation rate. Thus, binary pulsars are often called X-ray binaries. The flow of matter from the stellar companion, called the accretion disk, also glows in X-ray light owing to its high temperature. While some X-ray binaries are steady X-ray sources, others are bright only for a few weeks or months at a time, lying dormant for years between outbursts. The X-ray sky is thus highly variable, unlike the visible sky that we see at night.

X-ray binaries were first discovered by Dr. Riccardo Giacconi and collaborators in the early 1960s, with their binary nature established in the early 1970s by Giacconi and others. Giacconi was awarded the 2002 Nobel Prize in Physics for "pioneering discoveries in astrophysics, which have led to the discovery of cosmic X-ray sources."

The process of accretion can speed up the spin of a binary pulsar, since the high-velocity accreting material hits the pulsar at a grazing angle, constantly spinning it faster like a child's toy top. Rotation rates for such accretion-powered pulsars can reach hundreds of revolutions per second, or nearly once per millisecond. The transfer of material onto the neutron star also slowly cannibalizes the stellar companion so that, over millions of years, enough matter is accreted to completely whittle away a once healthy star. Scientists have found pulsars orbiting stars with as little as 10 Jupiter masses. One well-known example is the pulsar B1957+20, known as the "Black Widow" pulsar, which is emitting a stream of high-energy radiation that will soon blow away its now feeble companion so that no trace of this star remains.

There are many known isolated millisecond pulsars detected in the radio-wave regime. The fastest known is the pulsar B1937+21, spinning at an astonishing 640 revolutions per second. Scientists believe that these isolated millisecond radio pulsars were once X-ray binary millisecond pulsars that accreted material, spun up, and cannibalized their companions. This link was first confirmed in 1998 when scientists using the Rossi X-Ray Timing Explorer found that the X-ray binary millisecond pulsar SAX J1808.4-3658 was accreting matter from a companion with only 0.05 solar masses. Since then, astronomers have used the Rossi Explorer to discover four more accretion-powered millisecond pulsars.

The Galaxy is thought to contain about 100,000 pulsars, yet fewer than a thousand are known. Only a small fraction of these are millisecond pulsars. Isolated pulsars are hard to find because they are dim. X-ray binary millisecond pulsars are discovered when they flare up in a rare, sporadic accretion event that lasts only a few weeks. In many X-ray binaries, however, the accreted material on the neutron star is occasionally consumed in a violent thermonuclear explosion that sweeps across the surface, generating a bright burst of X-rays lasting a few seconds. Scientists using the Rossi Explorer in 1996 discovered rapid X-ray flickering during some of these explosions, called "X-ray burst oscillations," and suggested that this flickering might offer another way to measure the spin rates of neutron stars. An advantage of this approach is that burst oscillations are bright and fairly common.

New findings from the Rossi Explorer presented at the July 2, 2003, NASA Space Science Update confirmed that burst oscillations are a direct measure of a pulsar's spin frequency, or period. Essentially, scientists detected both steady millisecond pulses and burst oscillations simultaneously in the pulsar SAX J1808.4-3658, clinching the connection. This allows scientists to determine the spin rate of a large number of pulsars simply by measuring their burst oscillations, which is often much easier than detecting ordinary X-ray pulsations.

Using this technique, scientists have shown that of the 11 known pulsars with burst oscillations (called "nuclear-powered pulsars"), none spins faster than 619 revolutions per second, even though the Rossi

Explorer is capable of detecting spins as high as 4,000 revolutions per second. It is known that pulsars that spin too fast will break up and fly apart, and this is predicted to occur at a spin rate somewhere between 1,000 and 3,000 revolutions per second. From a statistical analysis of the 11 nuclear-powered pulsars, scientists have concluded that pulsars do not reach spins above 760 revolutions per second, which is well below the break-up point. Thus, they conclude, something intervenes to halt the pulsar spin-up well before break-up.

This finding supports the theoretical prediction of a feedback mechanism involving gravitational radiation limiting pulsar spins. Gravitational waves, analogous to waves upon an ocean, are ripples or distortions in four-dimensional spacetime. These waves, which were predicted by Einstein's theory of general relativity, are produced by the motion of massive bodies.

One possible explanation for the observed pulsar spin limit is the onset of gravitational radiation at high spin rates. Distortions in the neutron star can produce gravitational waves that carry away angular momentum, arresting the spin-up of the pulsar. The pulsar then reaches a new equilibrium spin rate where the rate of gravitational wave emission is exactly that needed to match the spin-up rate due to accretion of new material.

This explanation can eventually be tested through the direct detection of gravitational waves from these pulsars. Because the effects of gravitational waves are very subtle, however, distorting spacetime to alter the distance between the Earth and the Moon by less than the width of a single atom, they are very difficult to measure. Indeed, gravitational waves have never been directly detected, although there is considerable indirect evidence for their existence. Several experiments are now under way to directly detect gravitational waves. One of these is LIGO, the Laser Interferometer Gravitational-Wave Observatory, with detectors four kilometers in length located in Hanford, Washington, and Livingston, Louisiana.

The best indirect evidence for the existence of gravitational waves comes from analysis of the orbital decay of a binary radio pulsar by Dr. Russell Hulse and Prof. Joseph Taylor of Princeton University. Hulse and Taylor were awarded the 1993 Nobel Prize in Physics for this work.