NEUTRON STARS AND PULSARS

N.K. GLEDENNING
Nuclear Science Division, & Institute for Nuclear and Particle Astrophysics
Lawrence Berkeley National Laboratory, University of California
Berkeley, CA 94720, USA
NKGlendenning@lbl.gov

Discovery

Were it not for neutron stars neither we, nor the earth, nor any other planets would exist. Why do stars—so small that we cannot see them as we see other stars in the night sky—play such a singular role in the cosmic scheme? That is the story I tell.

The first neutron star was discovered quite by chance by Jocelyn Bell (Burnett) using a primitive antenna consisting of wires strung on stakes in a pasture near Cambridge University. With this antenna a faint but regular signal was detected—day after day. At first the team of researchers wondered if "little green men" from outer space were trying to contact earthlings. But Jocelyn Bell and Anthony Hewish soon realized they had stumbled onto a strange but natural phenomenon—a very small star about 10 kilometers in radius, but weighing as much as the Sun and spinning very rapidly. This was the kind of star that Walter Baade and Fritz Zwicky had proposed in 1934 as the remains of a luminous star at the end of its lifetime following its destruction in a supernova explosion.

Dick Manchester (Figure 1) in Australia now leads a large international team of astronomers from the UK, Australia, Italy and the USA in search for more of the surprises with which these stars have astonished us. Together, they have discovered more than half of all know pulsars. The Parkes radio telescope in Australia has just found the thousandth pulsar known to science. Andrew Lyne of the UK, and a member of the Parkes team, has made amazing discoveries, including central groups of many rapidly rotating neutron stars in globular clusters. Globulars are approximately spherical collections of a few hundred thousand stars that zoom back and forth through our galaxy like balls on a rubber string.

Today, at a few laboratories in both hemispheres, giant radio telescopes

Figure 1. Dick Manchester and Nicolo D'Amico, in the control room of the radio telescope at Parkes in Australia, reviewing evidence of a new pulsar. (Photo by John Sarkissian, Parkes Observatory, CSIRO

(Figure 3) are trained at the sky in a hunt for these strange neutron stars. It is believed that as many as 30,000 of them inhabit our Galaxy. Neutron stars, with one or two exceptions, make themselves "visible" to astronomers by a focused radio beam, which, because all stars rotate, appears, to the earthly astronomer like a pulsed signal—a lighthouse (Figure 2). Hence the name pulsar. Since the first discovery in 1967, there have been many surprises; the first pulsar with a sun's mass spinning 650 times a second discovered by Don Backer from UC Berkeley; the first extra-solar planetary system—three planets around a neutron star—discovered by Alex Wolszczan from Penn State and Dale Frail from the National Radio Astronomy Center, Socorro, New Mexico. Wolszczan and Frail used the worlds largest radio telescope (Figure 3) to detect signals coming from a distant tiny star in the constellation Virgo, 7,000 trillion miles from Earth. Many of these discoveries—besides revealing new wonders of our universe— have important consequences, none more so than the discovery by Russell Hulse and Joe Taylor in 1973 of a pair of neutron stars rapidly orbiting each other. By taking measurements on their orbital motion over a period of 25 years, Einstein's general relativity and the reality of gravitational radiation were confirmed to the one percent level. With every passing year additional measurements will either improve the agreement, or reveal a slight inadequacy in the theory, or less interesting, a perturbation not yet accounted for.

Figure 2. The Very Large Array of radio antennae in New Mexico. Among other radio objects in the universe these antennae have detected the pulsed radio emission from many pulsars. Credit: NRAO/AUI/NSF.

1 Birth, Death and Transfiguration

How does nature make these strange objects. That is the story of the birth, death and transfiguration of stars. The matter in the very early universe—before there were stars—was in the form of a diffuse gas of very light elements, about four parts of hydrogen and one of helium. The very lightest elements were formed in the first 10 minutes in the life of the universe. The heavier elements so important for life, like carbon, oxygen, and iron, had not yet been created, and would not appear until the first stars were born and died, a hundred million years later. Under the attraction of gravity, vast clouds of diffuse gas was pulled together to form galaxies filled

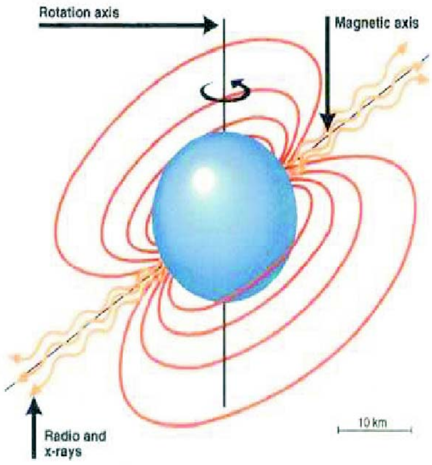

Figure 3. Schematic view of a rotating neutron star having a magnetic axis tilted from the rotation axis. Radio and other emission is beamed in a cone along the magnetic axis, and the star is detected as this cone sweeps past the observer, so that the star pulses—thus the name pulsar for such neutron stars. Credit: LBNL.

with stars. Stars are still being formed in great clouds of gas (such as the beautiful column shown in Figure 4) that occupy some of the space between the stars in our own galaxy, the Milky Way.

Stars like our sun are great furnaces. Our sun provides the warmth and energy by which we live. And like all furnaces, stars consume their fuel and burn out. The process known as thermonuclear fusion fires these furnaces. *Thermo* refers to heat, *nuclear* to nuclei, and *fusion* to the fusing of light elements into heavier. Three Helium nuclei are fused in a star to form Carbon; its mass is less than the three Heliums. According to Einstein's famous law $E = Mc^2$, the missing mass appears as radiant heat energy. Some of this heat energy is radiated into the universe, but the rest of it resists the force of gravity and holds the star up. A whole sequence of such burnings takes place involving the production of ever heavier nuclei until iron and nickel are made. The process ends here because the fusion of heavier nuclei does not put out energy; it requires an *input* of energy. In low mass stars, because gravity is weak, these processes proceed very slowly. Our sun will live for 12 billion years. But more massive stars—like the one that produced the only visible

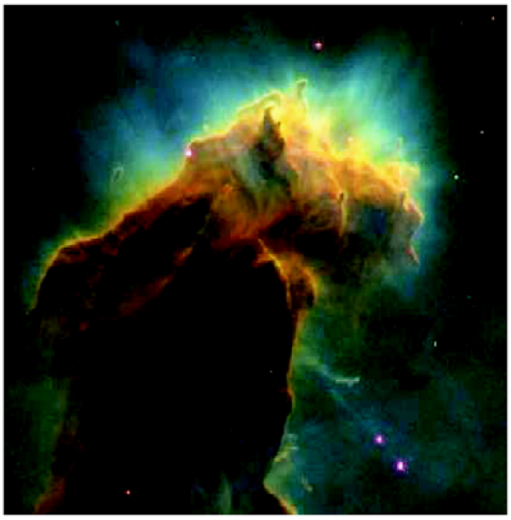

Figure 4. Birth: Parts of this great cloud of gas—called the Eagle Negula, many light years across—are being pulled together by gravity to form stars. Some of the star cradles are seen as bright nodules near the top of the column. Credit: Jeff Hester and Paul Scowen (Arizona State University), and NASA.

supernova in our lifetime—live for only 20 million years.

The iron that is produced as a star burns, sinks to the center and a limiting mass is finally reached—the Chandrasekhar limit—about one solar mass. At this point the inert iron core of a thousand kilometer radius can no longer resist its own gravity—it collapses in a second to a 10 kilometer very hot proto-neutron star leaving behind the rest of the star which then begins to collapse. But a burst of neutrinos is emitted by the hot neutron star in its final death throes. They carry an energy equal to ten times as much energy as the luminous star released in its entire lifetime of tens of millions of years. Even a small part of this energy is far more than enough to blow the rest of the star apart, and cast it off into space at 10,000 miles per second. The explosion is called a nova or a supernova. Supernovae and Novae (Figure 5)—the death of stars and birth of neutron stars or white dwarfs—can be seen even in very distant galaxies at the very limits to which we can presently see with powerful telescopes. At the peak of the explosion, the brightness equals tens of millions of suns, rivaling the brightness of their host galaxy. Even now the Crab nebula, a thousand year old supernova remnant, is as bright as

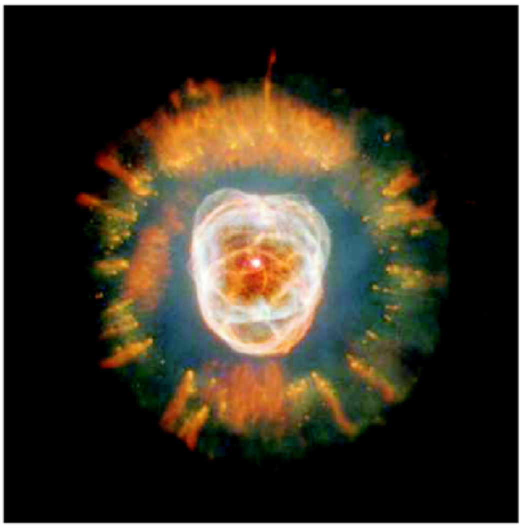

Figure 5. Death and Transfiguration: This planetary nebula (NGC 2392), called the Eskimo, began forming about 10,000 years ago when a star like our sun began to die. In its place at the center a nascent white dwarf is forming. Neutron stars and black holes are formed in more cataclysmic events than this. The glowing remains of the sun, first sighted by William Herschel in 1787, are being swept outward by winds from the hot white dwarf that have a speed of 115,000 kilometers per hour. Credits: NASA, ESA, Andrew Fruchter and the ERO team (STScI).

30,000 suns.

In the fiery cauldron of the expanding shell of cast off material containing the elements from Helium to Iron and Nickel that were manufactured in the original star during its 20 million year lifetime, all elements heavier than iron are forged in a few hours. They diffuse into the cosmos there to wander for eons, mixing with the gases of myriad other exploding stars and with the primeval clouds of Hydrogen and Helium to begin once again the cycle of star birth, transfiguration and death. Each generation of stars contains a richer mixture of the heavier elements. After many generations enough dust and heavy elements had accumulated in the host galaxy to form the first planets. On at least one of these, from the stuff of stars, life arose. About a hundred generations of stars have lived and died since the formation of our galaxy. So here we are to wonder at our own existence and the marvel of the cosmos.

But— occasionally, the neutrino burst does not cast away all of the outer part of the dying star. In this situation it falls back onto the neutron star, adding to its mass, sometimes to the point of exceeding the maximum that can be supported by the internal pressure against gravity. A black hole (Figure 6) is then formed from which nothing can ever return. Very massive stars—50 times the Suns mass—are believed always to form black holes. In this event, the elements that were manufactured during their lifetime are lost forever to the cosmos.

2 The Instruments

For centuries astronomers relied on electromagnetic waves, at first, exclusively the visible part of the spectrum using optical telescopes, sometimes built by themselves, such as Herschell's 48 inch reflecting telescope built with a grant from King George III. Today, the instruments used to search out and measure the radiations from neutron stars are many and varied and at a very high level of technology.

The Hubble Space Telescope that orbits the earth far above its atmosphere, carries instruments that probe many aspects of the universe. Infrared and X-rays "see" complementary aspects of star formation and their deaths. Many regions in space are hidden from optical telescopes because they are embedded in dense regions of gas and dust. However, infrared radiation, having wavelengths which are much longer than visible light, can pass through dusty regions. The center of our galaxy and regions of newly forming stars are very dusty and therefore opaque to the optical spectrum, but reveal themselves in the infrared.

Gravitational wave telescopes like LIGO and VIRGO and space-based telescopes like LISA open an entirely new window on the Universe. Einstein's theory tells us that the circular motion of any object, and especially very massive ones, create a disturbance in the fabric of space-time called gravitational radiation. Gravity waves can travel from distant reaches to provide details of colliding and coalescing neutron stars and black holes. In any one galaxy such events are extremely rare. But because these waves can reach us from many galaxies, both near and far, the chance of observing such events is greatly enhanced.

3 Theory and Experiment

If the size of our sun were represented by a hundred of these pages laid

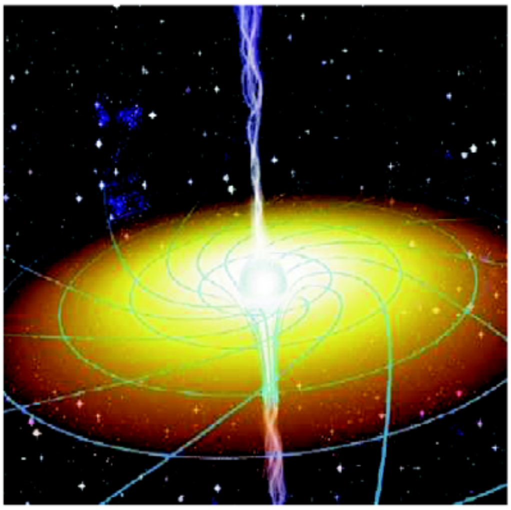

Figure 6. Artists conception of the distortion of space in the vicinity of a rotating black hole. For a star, the funnel would end as a rounded surface. Credit: Sky and Telescope.

end on end, the size of our earth would be about as long as this page and the size of a neutron star would be the period at the end of this sentence. Yet as much matter as resides in the sun is fitted into a neutron star. We need three physical theories to understand their dense interiors—relativity theory, nuclear theory, and quantum theory. *Relativity theory* is needed because so much mass occupies such a small space that space-time is warped. *Nuclear theory* is needed both because the crust on neutron stars is made of iron and nickel nuclei, and the pressure in the interior is so great that nuclei are torn apart into their individual nucleons. A considerable fraction of the nucleons themselves are likely transformed into other types of particles called hyperons, sometimes called *strange* nucleons. And in the central core of a neutron star these particles may be crushed and torn apart into the quarks, the most fundamental and indivisible particles, the long sought *atomos* of the ancient Greeks. *Quantum mechanics* is needed to properly understand this micro-world.

Strange as the interior world of neutron stars must be, by applying the laws of physics, we can arrive at some reasonable theoretical model of their interiors and test the model by observations made on these stars. Though we can never travel as far as a neutron star, and if we could we would be destroyed by gravity when we got close to one, there are observations and measurements that can be made with instruments here on earth. The masses of pulsars that have binary partners can usually be determined from measurement of the orbital parameters. This has been done very precisely for close binaries such as the Hulse–Taylor binary. According to theory, the mass of neutron stars has a maximum limit. This limit depends on the nature of the neutron star matter—on what is called the *equation of state*. Determination of neutron star masses thus places constraints on the theory of neutron star matter.

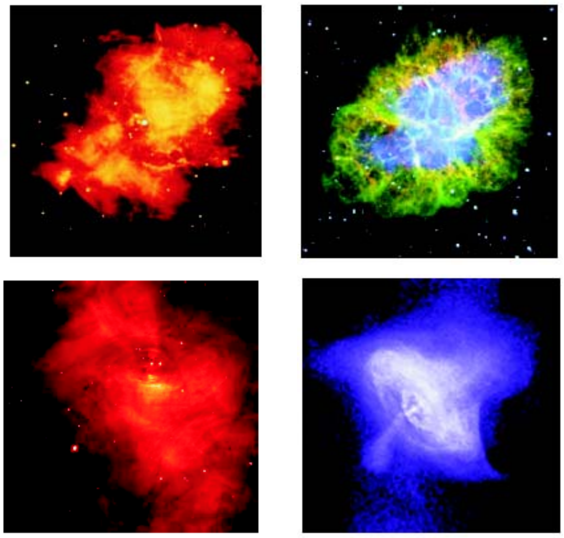

Figure 7. Four different views of the Crab supernova remnant. The first and last are taken at infrared and x-ray frequencies, the center two at optical, one with a ground based telescope, the other with the Hubble Space Telescope showing the central region of the crab nebula. The neutron star is at the center of a sort of whirlpool diagonally to the right and up. The fourth view, at x-ray frequency, is also a view of the central region that reveals one end of a jet expelled by the neutron star rotating 30 times a second. The other end is faintly visible and apparently deflected, possibly by a shock wave from another explosion far away. Credit: NASA.

The rate of rotation of pulsars is so precise that some are known as the best timekeepers in the universe. However, every so often the rotation rate suddenly increases. It is thought that these *glitches* are related to a very special form that the interior of the neutron matter takes—a superfluid state.

This state allows the neutrons to flow without friction. A superfluid can only rotate by forming quantized vortices, where the number of vortices per unit area is proportional to the rotation rate. Lines of vortices move outwards from the center of the star, reducing the vortex density and hence the rotation rate of the superfluid. The mismatch between the rotation rate of the solid crust of iron and nickel, and the superfluid is thought to cause random *glitches* in the rotation rate of the star. In this way, very intimate internal pulsar properties are related to the observable glitching.

The RHIC relativistic nuclear collider at Brookhaven and the LHC hadron collider at CERN Geneva were built precisely to investigate the micro-world which inhabits neutron star interiors. And satellites put into orbit around the earth, like the Hubble Space Telescope, have the power to reveal their habitats. During the 15 years that I have been interested in this area of theoretical physics, progress in instrumentation, in computers, and in the growth of data, has been staggering. In a very real sense, scientists are using neutron stars to study the nature of matter under extreme conditions that complement but does not duplicate what can be learned in an earthly laboratory.

More recent publications of the author on the topics of this contribution:

References

1. ON THE POSSIBILITY OF DETECTING PHASE TRANSITIONS IN THE CORES OF ACCRETING X-RAY NEUTRON STARS, N.K. Glendenning, *J. Phys.* **G28**, 2023-2027 (2002).
2. PHYSICS OF NEUTRON STAR INTERIORS, Lect. Notes Phys. 578 (2001) 1-509.
3. PHASE TRANSITIONS AND CRYSTALLINE STRUCTURES IN NEUTRON STAR CORES, N.K. Glendenning, *Phys. Rept.* **342**, 393-447 (2001).
4. ON THE UNCERTAINTY OF HYPERON COUPLINGS AND THE ELECTROCHEMICAL POTENTIAL IN NEUTRON STAR MATTER, *Phys. Rev.* **C64:025801** (2001).
5. POSSIBLE EVIDENCE OF QUARK MATTER IN NEUTRON STAR X-RAY BINARIES, Norman K. Glendenning, F. Weber, *Astrophys. J.* **559:L119** (2001).
6. MODEL INDEPENDENT MASS RADIUS CONSTRAINT FOR NEUTRON STARS, Norman K. Glendenning, *Phys. Rev. Lett.* **85:1150** (2000).
7. SURFACE TENSION BETWEEN KAON CONDENSATE AND NORMAL NUCLEAR MATTER PHASE, Michael B. Christiansen, Norman K. Glendenning, Jurgen Schaffner-Bielich, *Phys. Rev.* **C62:025804** (2000).