Guest Star

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Supernova 1987A

On February 23, 1987, at the Las Campanas Observatory in Chile, Oscar Duhalde and Ian Shelton discovered a new star in the Large Magellanic Cloud, the brightest, nearest galaxy to our own Milky Way. The star was bright enough to be seen with the unaided eye. It was later realized that 19 neutrinos from the same star (11 in Kamiokande, Japan, and 8 under Lake Erie) had been detected earlier that same day in giant water tank detectors looking for proton decay.

What did this mean? Why was it so important? People often ask me if I have discovered any new stars lately. When you stop to think that our own Milky Way galaxy has over 100 billion stars, and that a similar number of galaxies are in principle observable, you realize immediately that simply discovering another star like our sun, for example, is not necessarily very important (it's like "discovering" one more corn stalk in a large field). But when a new star appears in the sky that can be seen without a telescope and may even rival the moon in brightness, we are talking about another kind of event.

Tonight I would like to describe why this was such an important event and why it had consequences far beyond what one might think at first sight. I will show that the light from the new star was produced by the most violent explosion that occurs in the universe, one that rips an entire star apart and blows all its material into space, except for a tiny core that represents the most extreme conditions in the present-day universe. I will also show that the explosion has a surprising connection to the age-old question of where did we come from (more specifically, where did the atoms of which we are made come from).

Tycho

To appreciate the background of Duhalde's and Shelton's discovery, let me go back to Denmark in the year 1572, the time and place of one of the most famous astronomers of all time, Tycho Brahe. Tycho is famous on at least three counts: 1) he developed new instruments that could measure the positions of stars and planets much more accurately than could be done previously and used them to make observations that were the basis from which Kepler derived his laws of planetary motion (and which led to Newton's laws of motion and gravity and the basis for today's space programs); 2) he built the first great observatory, from which today's large observatories are descended; and 3) he discovered on November 11, 1572 a new star near the constellation Cassiopeia which attained the brightness of the planet Venus. The discovery of the new star was what laid the basis for his fame and successive work.

Tycho studied alchemy and astrology, as was the custom of his time. Indeed, I suspect it was the astrology as much as anything that had to do with his fame and support from the

King of Denmark. Alchemy, recall, covered efforts to transmute common metals into gold, and I gather, provided some of the basis for modern chemistry. Of course, we now know that it is not possible to transmute elements by chemical processes.

Tycho was hardly a "nerd" in his day; rather he had a flamboyant life. His nose was cut off in a duel during his student years, and he sported a replacement nose made of gold, silver, and enamel in later life. After he became famous, he obtained support from the King that is said to have been the equivalent of 1% of the gross national product and used it to build his famous Uraniborg observatory on the island of Hven, off the coast from Copenhagen (and a wonderful place to tour today). To my knowledge, he must hold the all time record for success in fund raising in our field. It is said that his retinue included a dwarf, Jeppe, whom he used to feed table scraps during the great parties Tycho offered. And, he treated his serfs very badly all the while trying to get even more support from the King. His situation reached the point that he had to leave Denmark after the King died and his son refused to continue to support Tycho so lavishly.

To return to the main part of our subject, Tycho's discovery of the new star changed people's view of the universe at that time. Evidently stars were not unchanging. And, as I mentioned, his careful and systematic observations were carried out very much in the style of modern science, and they turned out to have far-reaching consequences for our modern world. What I also find interesting and perhaps not so obvious, is the connection we now know exists between his "new star" and "alchemy" (which in today's science I will call the subject of how the elements formed). As we shall see, the "new stars" play a fundamental part in our own existence. They are not just astronomical curiosities.

The Nature of Stars

To fill out the story and make the connection between the new star found in 1987 and the one found by Tycho, let me summarize some of what we know about stars today. The sun comes up, the sun goes down. That's not news. What's the big deal? Let me remind you first of all that we would not be here without the sun. If the sun happened to go out, we would find out only too quickly what it is like when hell freezes over. Fortunately, the sun has been around for four and half billion years without changing too much, and it has another four and a half billion years to go, so we need not lose sleep on that account.

I think that the one of the intellectual triumphs of our century has been understanding the structure and evolution of the stars. While that is a subject for a whole book in itself, a main point that concerns us here is that the sun and stars are powered by nuclear energy, more precisely by thermonuclear reactions that fuse nuclei together, release tremendous amounts of energy (compared to chemical reactions), and result in the production of new elements. For example, the main reactions in the sun produce one helium nucleus from four protons (hydrogen nuclei). Although we are making a huge investment, we are so far not able to maintain similar reactions here on earth to what the sun is routinely doing day after day and millennium after millennium. Why is that?

One of the main reasons is that the sun has enough mass (and gravity) not only to hold itself together but to produce very high temperatures and pressures in its center. These are the conditions needed both to initiate and contain nuclear reactions, whose tremendous heat tends to blow apart the gas in the laboratory when we try to duplicate the reactions here on earth. Indeed, one way to appreciate the difficulty is to consider that we are trying to control the reactions that occur in the hydrogen bomb.

Stellar evolution can be chronicled as the contest of gravity against gas pressure. Gravity inexorably pulls stars together, trying to shrink them evermore. But, as they do contract under gravity, their central temperatures and pressures rise to the point that nuclear reactions can be sustained. The reactions produce enough energy to maintain the central temperature, to resist the pull of gravity, and to produce the energy that we see in the sun and other stars. The energy, which is 0.7% of the rest energy of the fuel, is a very practical demonstration and benefit of Einstein's famous $E = mc^2$ relation. The energy is so great that it can power the sun for about 10 billion years and allow life to develop and evolve.

But the source of energy is not infinite. Hydrogen is being converted to helium at the center of the sun, and eventually the hydrogen will be exhausted. What then? Gravity resumes its pull (this is like a medieval torture chamber) and the center of the star heats up some more. Eventually, the temperature will rise to the point that helium nuclei can start fusing together to form carbon. Fortunately we won't be around at that time. This reaction will occur very quickly, indeed almost explosively. The sun will increase in size so that it almost reaches the orbit of the earth. Although its outer layers will cool somewhat in the process, the overall luminosity of the sun will increase by nearly a thousand times, and the earth as we know it will disappear, most likely vaporized. Although dramatic enough, the end of the sun will be tame compared to what happens to stars that weigh more than ten times the mass of the sun.

The gravitational effects in such stars are much greater than in the sun, and the consequences in the end are nearly unimaginable. But at the beginning, these stars are not so different qualitatively from the sun except in one aspect - they are much more luminous, and they have much shorter lifetimes, as short as a few million years. They are the cosmic Roman candles.

Let us follow their evolution. At first, they convert hydrogen to helium, just like the sun, although by reactions that involve carbon, nitrogen, and oxygen. Time does not permit covering all the details, but we can use the general principle that as one source of fuel is exhausted at the center, the star contracts and heats up until another reaction can begin. This has the interesting consequence that the central regions take on an onion-like structure, with hydrogen at the skin, then layers of helium, carbon, oxygen, and so on toward the center. As the evolution plays out, the physical conditions at the center take on values that are unimaginable by our daily experience. The central temperature climbs to over a billion degrees, and the density to millions of times greater than water. Eventually, an interesting characteristic of atomic nuclei becomes crucial. As successively heavier nuclei are built up in the center of the star, they release proportionally less energy in the thermonuclear reactions. When finally iron is produced, we have reached the bottom of the well - further reactions do not release energy, they require it to be put in from some source.

At this point the star has a real problem, as would any inhabitants of hypothetical planets in orbit around the star. It has run out of fuel! But its surface layers are still radiating energy furiously, which causes it to cool, and the inexorable force of gravity keeps compressing the center. What happens?

Collapse!

There happens to be a seemingly magical limit called the Chandrasekhar limit that says that dead stars with masses greater than 1.44 times that of the sun cannot support themselves against gravity. It also happens that stars of 10 solar masses or greater can produce iron cores near this limit as they end their lifetime. As long as the core mass is below the limit, everything is OK, but once the limit is exceeded, the core can no longer hold itself up.

I should add that the size of this core is about the size of the earth; indeed the end point of the sun's life will be as a so-called white dwarf star, which has about the mass of one sun packed into the volume of the earth. Talk about high density! No wonder it is called degenerate matter. In the case of massive stars, their outer envelopes can be much larger than the size of the sun, even though they have this comparatively tiny core at their center. All the action is about to occur at the center, but it will be some time before the outer layers know what happened.

Returning to our massive star, at some point matter will continue to get squeezed into the central core until it reaches the Chandrasekhar limit. At this point, it can no longer hold itself up against gravity, and begins to collapse under its own weight. The most dramatic event in the universe begins!

What actually happens during the collapse of the iron core remains one of the most challenging problems in astrophysics, both for the range of complicated effects that occur and because the extreme conditions exceed in some areas our current knowledge of physics. Thus, let me mention some of the highlights and the points about which we are reasonably confident.

There is no doubt that the collapse is very rapid - it occurs at a significant fraction of the speed of light. Furthermore, the density of matter increases very rapidly and reaches the level of the atomic nucleus, some 10^{15} times that of water. Ordinary nuclei are torn apart (after having been built up so laboriously in the preceding reactions), and the particles are converted to neutrons. About 10% of the rest energy of the core is liberated by the gravitational contraction (another irony - gravity, the weakest force, succeeds in liberating more energy than is possible from nuclear reactions). This energy momentarily makes the power output from the core as great as from all the stars in all the galaxies in the visible universe! Then, once the density does reach the level of the atomic nucleus and the nuclear particles are converted to neutrons, the core can finally resist further collapse - it can hold itself up against gravity again. But now it is only about the size of Columbus, and all the material from above is still raining down at some appreciable part of the speed of light. What happens next?

Rebound and Explosion

We get the most stupendous rebound imaginable. All the energy I mentioned above is trying to get out, and the matter has to bounce back! A tremendous, violently explosive shock wave starts at the center and moves out towards the surface of the star, carrying everything along with it. In brief, everything outside the dense core explodes. Interestingly, it takes hours for the shock wave to travel outward and reach the surface. Until then, there is no visible evidence of the collapse of the core and resulting explosion.

However, there are particles that can escape from the center almost immediately after the core collapse and rebound. These are the ghostly neutrinos, perhaps the most unusual particles in physics. They can pass through the earth, the sun, in fact a light year of lead, almost as if they were not there, but it turns out that in the extreme conditions of supernovae, they wind up carrying away most of the energy. Because they do come out almost immediately after the explosion, they carry crucial clues about what happened.

Therefore, it was their detection in February of 1987, hours ahead of the light from the supernovae being seen, that provided the main confirmation that the story I have just described is roughly correct.

Once the shock wave does reach the surface of the star, then we begin to *see* the effects of the explosion - the star brightens rapidly as it is torn apart. Within days it can become as bright in visible light as an entire galaxy - it reaches the luminosity of nearly 10 billion suns. The star is literally blown apart, and its matter is blasted into space at speeds of 5,000 miles a second.

Supernova

Thus, what Oscar Duhalde and Ian Shelton saw in Chile on February 23, 1987 was the breakout of the shock wave on the surface of the star in the Large Magellanic Cloud whose core had collapsed earlier and emitted the neutrinos detected under Lake Erie and in Japan. They were the first to see the brightest supernova since 1604, one that would eventually reach 2^{nd} magnitude in apparent brightness and be visible without a telescope for months. Their discovery initiated feverish work by astronomers all over the world to observe the supernova and learn what had really happened.

The Large Magellanic Cloud is at a distance of about 170,000 light years from the Earth (for reference, the nearest star is about 4 light years away, and the Milky Way is about 100,000 light years across). The Large Magellanic Cloud, and its companion, the Small Magellanic Cloud, are often called the Rosetta Stones of astronomy, because they are so near and because they can be studied in great detail. A key factor in their importance is that we know their distance accurately, something that is not usually the case for stars in our own Milky Way.

By 1987 the Large Magellanic Cloud had been extensively mapped and studied, and astronomers soon realized they could identify exactly which star had blown up, a first in the study of supernova. This is where the Rosetta Stone part of the story came in. By measuring the position of the supernova accurately, astronomers determined that its precursor was a 12^{th} magnitude, blue star, that had been about 50 times larger than the sun. From knowledge of how stars evolve, we believe this star began life with a mass about 20 times that of the sun, ejected during its 10 million year lifetime maybe 5 solar masses as clouds of gas into space surrounding the star, and then underwent core collapse as it exhausted its nuclear fuel. After core collapse, the entire star blew up and is now ejecting its matter back into space.

Guest Stars

Prior to 1987, we have records of only five naked-eye supernovae in this millennium. They occurred in the years 1006, 1054, 1181, 1572, and 1604. The Chinese kept some of the best historical records, especially during the Dark Ages in Western Europe, and their records have played an important part in our understanding of the historical supernovae.

The reason I chose my title is that we translate the Chinese words for the new stars as "guest stars".

Christmas Star

During this holiday season we recall that the wise men cited by Matthew in the New Testament remarked on the star of the east that marked the birth of Jesus. There has been speculation that they were seeing a supernova. Although a supernova is no longer believed to be the correct explanation, you can now imagine why it has been mentioned as a possibility.

Where Did We Come From?

Supernovae turn out to be key events in the death and rebirth of stars and indeed of ourselves. We would not exist without them. Supernovae play two key roles in the evolution of our galaxy. The titanic explosion that marks the end of the life of a massive star not only rips it apart and flings its matter back into space, but it also produces many of the elements from which we are made. The energy is so great during the explosion that a panoply of nuclear reactions occur which especially build up elements heavier than iron, like gold, for example. What the alchemists labored so hard to accomplish, transmute common elements into gold, supernovae do in a literal flash. We now know that essentially all the elements on earth heavier than hydrogen and helium were produced in stars and supernovae. That is what I mean when I say we would not be here without them.

The blast wave of supernovae has another surprising effect. In addition to producing chemical elements and ejecting them back into interstellar space, the wave is believed to trigger the formation of new stars when it encounters other clouds of gas between the stars. Thus, supernovae are both the suppliers of the heavy elements from which we are made and the initiators of new generations of stars.

I like to say that supernovae are the ultimate in recycling.

After the Explosion

Although most events in astronomy happen on time scales far longer than our lifetime, supernovae are clearly an exception. The collapse and central explosion occur in about a second. What next? Although time does not permit much of a discussion, you may be interested to know that the remnant of the explosion in many cases is a neutron star, an object that weighs about as much as the Sun and yet has a radius of only six miles, about the size of Columbus. It contains matter in its most extreme condition, that of the atomic nucleus. Neutron stars are the densest objects known in the universe and have such a strong gravitational pull that even light can only barely escape from their surfaces. Neutron stars in general rotate very rapidly, making tens to hundreds of rotations per second. Many of them seem to have exceedingly strong magnetic fields that produce a rotating searchlight effect of radio radiation. When the beam of radio radiation happens to point at the earth we see them as pulsars, producing radio signals with a regularity that rivals or exceeds the best atomic clocks we have on earth.

In the meantime the matter ejected from the supernova travels outward into space and produces a rapidly expanding cloud of gas that is lit up by the shock wave and energy of the explosion itself, by radioactive material in the cloud that decays and liberates more energy, and by the remnant pulsar I just described. One of the best known cases of such a cloud is the famous Crab Nebula in the constellation Taurus, which was produced by the guest star seen by the Chinese in 1054. The gas in this nebula is expanding outward at speeds of about 1000 kilometers per second, and in the 900 or so years since the explosion has expanded to a size more than 200 times the diameter of the earth's orbit. This nebula can be seen in a small telescope; it has been one of the keys to our understanding of what happens after a supernova explosion. And, it also contains the famous Crab pulsar, which is rotating 30 times a second and provides some of the energy currently powering the nebula.

Thus, the Chinese guest star of 1054 has spanned virtually the entire era of modern astronomy and is on its way to becoming a millennial object itself.

Summary

The "guest stars" turn out to be the final explosions marking the death of stars. But they provide a way of producing the elements from which the earth is made and for reseeding interstellar space. And, they trigger the formation of new stars. The rebirth they represent is an appropriate theme for the holiday season.

References

Laurence A. Marschall, "The Supernova Story," 1994, Princeton University Press. This is a very readable, non-technical account of supernovae from which I have drawn much of the information for this essay.

David A. Arnett, "Supernovae and Nucleosynthesis," 1996, Princeton University Press. A highly technical book, this is a tour de force that covers much of modern astrophysics as it describes the accomplishments and challenges still facing supernova research. I have referred to it for some of the technical aspects of the essay.