INTRODUCTION TO SUPERNOVAE

According to the Annals of the Sung Dynasty (the Sung-shih), on the first day of the chi-ho reign period, during the 5th month, on the chi-chou, a "guest star" appeared to the south east of Tian-kuan. The guest star was so bright that it could be seen during the daytime, and it remained so for 23 days. After that, it gradually dimmed, finally fading from visibility after two years. Japanese records also mention the star.

An unknown artist may have recreated the appearance of the Crab Nebula supernova in 1054 on the side of a cave wall in Chaco Canyon, New Mexico.

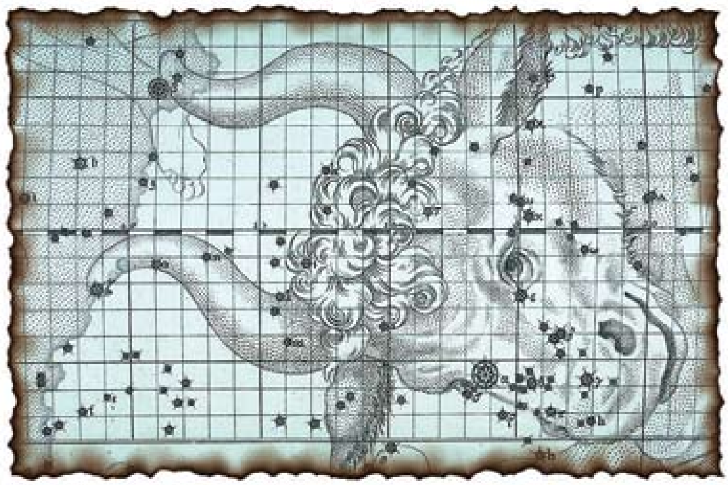
At around the same time, half a world away from China in what we now call Chaco Canyon, in Northern New Mexico, an ancestor of today's Hopi and Navajo painted what appears to be a "guest star" into a protected rock overhang. The star is shown next to the crescent moon, and a hand print, perhaps that of the artist, is also painted on the rock. Though this record is not as detailed as that of the Sung astronomers, the orientation of the moon and the guest star is what it would have been on that day when the Sung reported their guest star, strongly suggesting that the two are the same.

Such an impressive object, recorded in disparate cultures around the globe, must have been visible in Europe as well as Asia and North America. However, the date given in the Chinese annuls, by our modern reckoning, would have been July 4, 1054. At that time Europeans were in the throes of the Dark Ages, and the Norman Invasion was just a few years away. Perhaps they were too occupied with worldly concerns to mark down the appearance of a celestial visitor, or perhaps whatever record existed has been lost. In any case, no European record of the event has ever been found.

Since the appearance nearly a millennium ago of the Sung "guest star" there have been only two other similar objects seen in our **Galaxy**. One occurred in 1572 in the constellation Cassiopeia. This was observed by the Danish astronomer Tycho Brahe and bears his name. It became bright enough to be visible in full daylight. The other star appeared in the constellation Ophiuchus in 1604 and was studied by Tycho's student and collaborator, Johannes Kepler, though it was seen earlier by several other people. Kepler's star, while not as bright as Tycho's, was still as bright as Jupiter. Since the appearance of Kepler's star, no others have been seen in the Galaxy.

This does not mean, however, that no additional similar objects have been observed. In 1885 a new star appeared in the center of the Milky Way's companion galaxy M31, in the constellation of Andromeda. It reached a peak brightness of 6-7th **magnitude**, making it easily visible in small telescopes against the background glow of the galaxy itself. The object is important for historical reasons because it was used to argue, incorrectly, that the great spiral nebula of Andromeda was a new star system, like our **solar system**, in the process of forming within our own galaxy. The astronomer Harlow Shapley, in a famous 1922 debate with Heber Curtis on the nature of the spiral nebulae, claimed that the appearance of the guest star in Andromeda was due to a "new sun" just beginning to turn on. His argument was later shown to be wrong. Edwin Hubble measured the distance to the Andromeda nebula and proved it was extremely far away and, in fact, an independent system of stars – a galaxy on a par with our own Milky Way.

Though these guest stars are rare events in any given galaxy, the universe



The Crab Nebula is located just above the star marking the tip of the lower horn of Taurus, the Bull.

contains many, many galaxies. With the advent of large telescopes in the 1920s and 30s it was soon noticed that guest stars could be seen quite often if one looked at many galaxies. The fact that the guest stars were nearly as bright as the galaxies in which they occurred meant that they were enormously energetic. Their great brightness and release of energy prompted the astronomer Fritz Zwicky to dub them **supernovae**, because they appeared similar to, but far brighter than, the "novae" seen in our galaxy. Supernova is the name by which we still call them today, though we now know they have nothing in common with novae except a name: supernovae are exploding stars, whereas novae are the much smaller explosion of the atmosphere of a **white dwarf** star that is acquiring matter from a nearby binary companion star. *(For more about supernova life cycle, see p.8.)*

In an ironic twist, recent observations of supernovae similar to the one seen in Andromeda in 1885 have allowed us to measure the vast size and expansion rate of the universe. To our great surprise, these extremely distant supernovae indicate that the expansion is accelerating, rather than slowing down. These observations indicate that approximately 70% of the energy in the universe is something never before observed, with properties heretofore only imagined in the most speculative of our theories of nature. Far from showing that the universe is small, as Shapley argued, supernovae have shown us that the universe is not only vast, but much stranger than we had imagined.

If you point a telescope toward the patch of sky described in the Chinese records from 1054, just a few degrees north and east of Aldebaran, the "eye" of Taurus, the bull, you will find a faintly glowing cloud. This is the Crab Nebula. It is the remains of a star that exploded some 7000 years ago. The explosion was seen on Earth only 1000 years ago because it was so distant that its light required 6000 years to reach us; the Sung and Chaco Canyon inhabitants were seeing the explosion 6000 years after it happened. The Crab Nebula is a **supernova remnant**, the debris from an exploded star. It is still expanding today at more than 1000 km/s, (for more about supernova expansion see p.11) having slowed from an initial expansion speed of more than 10,000 km/s. Inside the nebula is the Crab pulsar, the compact remnant of the core of the exploded star. The pulsar is a highly magnetized, rapidly spinning **neutron** star, a class of object that is among the most bizarre found in nature. A mere teaspoon of the crab pulsar would weigh more than a billion tons (for more about neutron stars see p.22.)

In the remainder of this education unit, you will explore the amazing properties of supernovae and neutron stars. You will also begin to learn about some of the tools scientists use to understand them.

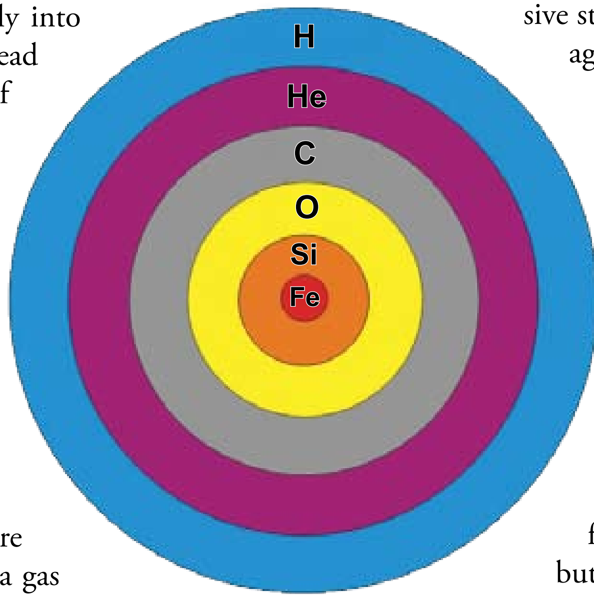
WHY STARS EXPLODE

The stars in the sky seem eternal and unchanging.

But that's an illusion. Like all things, stars are born, live out their lives, and eventually die, doomed to fade away. Stars like the Sun, which have a relatively low mass, age gracefully and die quietly after billions of years. But massive stars, with more than ten or so times the mass of the Sun, "do not go gently into that good night, but instead rage, rage against the dying of the light". They explode in a catastrophic detonation, sending their outer layers screaming outwards at a few percent of the speed of light: what astronomers call a supernova.

The seeds of a star's ultimate destruction are planted deep in its core, where its energy is generated. Stars are giant balls of gas, and when a gas is compressed it heats up. Because stars are so big they have a lot of gravity, so at the core of a star the pressure is intense. This means they get very hot, hot enough to smash together **atomic nuclei**. And when nuclei collide, they can stick together in a process called fusion. This process releases a lot of energy (in fact, it's what makes hydrogen bombs explode), which heats up the core. In a stable star like the Sun, the inward crush of gravity is balanced by outward pressure caused by the heat.

Already we see that the mass of the star is important: it provides the gravity needed to compress the core. The higher the mass of the star, the more the core is compressed, and the hotter it can get. Fusion reactions depend strongly on temperature; the higher the temperature, the faster the reaction proceeds. As we'll see, this is critical later in the star's life.



Near the end of a massive star's life, the fusion occurs in shells around the core, like the layers of an onion.

Initially, the star fuses hydrogen into helium. Like ash in a fire, the helium builds up in the core, but it does not fuse because helium takes a lot more pressure and heat than hydrogen does to fuse. If the star is massive enough, though, it can ignite helium fusion in its core. The helium fuses into carbon, which then starts to pile up in the core. In very massive stars this process repeats again and again, fusing lighter elements into heavier ones: hydrogen to helium, helium to carbon, carbon to neon, neon to oxygen, oxygen to silicon, silicon to iron. The star's core starts to look like an onion, with layers nested inside one another.

At every step, the process generates more heat, and the fusion goes ever faster. A star may fuse hydrogen into helium for millions or billions of years, but by the time it starts to fuse silicon into iron, it may take mere days. As iron piles up in the core, the star is headed for disaster.

Why? Because up until iron, all the fusion reactions have produced energy in the form of heat. That heat holds the star up. However, iron is different. It takes energy to fuse iron into heavier elements, and this energy must come from the star itself. When enough iron builds up in the core, the pressure becomes great enough that it starts to fuse. This robs energy from the star, cooling it. Worse, the fusion of iron eats up copious amounts of **electrons**, and the motion of these electrons was helping to hold up the star too.

When iron starts to fuse, things go bad fast. The iron core collapses, since the heat and electrons holding it up get used to fuse the iron. In a thousandth of a second the tremendous gravity of the core collapses it down from thousands of kilometers across to a ball of compressed matter just a few kilometers in diameter. This is a bit like kicking the legs out from under a table. Just like when Wile E. Coyote suddenly realizes he is no longer over solid ground and starts to fall, the outer layers of the star come rushing down. They slam into the compressed core at a significant fraction of the speed of light.

These pictures shows the location of Supernova 1987a before it exploded (left), and during the explosion (right)

This does two things: it sets up a huge rebound, sending the outer layers of the star back out, and also releases a vast number of neutrinos, subatomic particles that carry away most of the energy of the collapse. The gas from the outer layers absorbs only a small fraction of these neutrinos, but that's still a lot of energy: it's like lighting a match in a fireworks factory. The outer layers of the star explode upwards, and several **solar masses** of doomed star (containing the elements that were produced before the explosion) tear outwards at speeds of many thousands of kilometers per second.

As the star explodes, the expanding gas is so hot that it can undergo temporary fusion, creating elements as heavy as uranium. This, plus other **radioactive** elements created in the explosion, dumps even more energy into the gas, causing it to glow. The expanding gas is called a supernova remnant; it will expand for hundreds of thousands of years, eventually cooling and becoming so thin it merges with the tenuous gas between the stars. Sometimes the gas from the remnant will hit and mix with gas that is forming new stars, seeding it with the heavy elements formed in the explosion. The iron in your blood and the calcium in your bones were formed in the supernova explosion of a massive star millions of years before the formation of the Earth itself.

And what of the core? Like the life of the star itself, the fate of the core depends on its mass. In relatively low-mass stars like the Sun, the star never explodes at all. The core is not massive enough to fuse helium, so helium simply builds up. Or perhaps helium does fuse, but then the star is not massive enough to fuse the resulting carbon. In any event, the outer layers of the star are blown off by a solar wind over millions of years, and the naked core, unable to generate its own heat, simply cools and fades away. A star that consists of this revealed core is called a white dwarf.

If the core is more massive, between 1 and 3 times the Sun's mass then things are different. The pressure from the collapse slams electrons into protons, creating neutrons. The core shrinks to a size of a few kilometers across, and is comprised almost totally of these neutrons. The collapse is halted by the neutrons themselves, which resist the pressure. Not surprisingly, this object is called a neutron star.

And for more massive cores? Even the neutrons cannot resist the pressure created by more than about 3 times the Sun's mass when it collapses. The core implodes, and nothing can stop it. Its gravity increases hugely, and anything that gets too close will be drawn in, even light. It has become a black hole.

David De Martin (http://www.skyfactory.org), Digitized Sky Survey.

This is more than just theory. By studying supernovae, supernova remnants, and other exotic objects, astronomers have discovered all this and much more. If you want to continue reading about this and get more information, check out the Resources list in the last section of this poster.

Description of the Illustrations

The following images provide an artistic rendering of emission from a supernova remnant in three different energy regimes: optical, x-ray and gamma radiation. While the overall shape of the remnant is the same in each energy band, the processes underlying the emission can be quite different.

The first and second images show emission mostly from gas at the edge of the remnant. As the ejected material from the supernova encounters gas that already existed around the star, it creates shock waves, similar to the way a supersonic jet makes shock waves in the air. Inside these shocks the gas ejected from the exploded star is slowed, compressed, and heated to millions of degrees. This happens because, as the expanding supernova material collides with the existing gas surrounding the star, its kinetic energy – the energy of its motion outward from the supernova – is converted to random motions, called turbulence. The high temperature of the gas means the atoms are moving very rapidly, which leads to very energetic collisions between them. The collisions are so energetic that they kick electrons completely off of the atoms, that is, the atoms become ionized. When gas is this hot, the atoms bounce off each other at high speeds, generating X-rays. Image 2 in the large panels on the front of the poster depicts this sort of emission.

Optical view

As the remnant emits X-rays it loses energy. After all, X-rays are a form of radiation, like optical light, so they carry away a lot of the energy of the supernova into space. That loss of energy causes the remnant to cool. After several tens of thousands of years the outer shocked part of the remnant has cooled to only a few thousand degrees. Gas at this temperature is not hot enough to produce strong X-ray emission, but it is hot enough to excite (give energy to) the atoms within it. When an atom absorbs energy, its electrons jump from one energy level to another, like someone going up a staircase. After some time, the electron then falls back down to a lower level, and emits energy at a very specific wavelength. This type of emission is called line emission. In a low density but hot gas like that of an old supernova remnant, the emission lines typically seen are from excited and ionized forms of hydrogen, oxygen, nitrogen, sulfur, and other kinds of atoms. This can make supernova remnants appear to our eyes to glow with characteristic colors such as red or green.

X-ray view

This lower-temperature gas tends to be from the outer parts of the supernova remnant. The inner part of the remnant is still filled with million degree x-ray emitting gas. This is because the density inside the remnant is much lower than in the outer shocked parts, and the lower density causes the inner part of the remnant to cool much more slowly. In fact, it takes more than a million years for the hot bubble inside a supernova remnant to cool completely. Because these two types of emission depend on the temperature of the gas emitting them, they are sometimes collectively called thermal emission.

Gamma-ray view

The last frame in the poster depicts a different type of radiation process entirely. This image shows the emission of gamma rays, the most energetic type of electromagnetic radiation. The gamma rays are not emitted by the gas itself because even a million degrees is not hot enough to produce gamma rays. Instead, the emission is produced by the interaction of the electrons in the remnant with the magnetic field of the compact neutron star in its center.

This neutron star is the remains of the core of the star that collapsed. The neutron star is fantastically small and dense: while it's only a few kilometers across, a single teaspoon of neutron star material weighs as much as 100 million adult elephants, or a mountain a kilometer high! It spins rapidly, up to thousands of times per second, and can possess extremely strong magnetic fields. As the star's spin sweeps its magnetic field through the remnant, it picks up charged particles such as electrons like a fisherman's net sweeps up fish. These particles are accelerated to speeds close to the speed of light as they ride along with the magnetic field.

When charged particles are accelerated like this, they emit radiation. However, the radiation is very different from the emission described for the first two panels. This type of emission, called synchrotron emission, does not come out at one specific energy. Rather it is seen in a very broad, nearly flat continuous spectrum, spanning all the way from radio waves to gamma rays. Furthermore, in contrast to emission lines and thermal X-rays, synchrotron emission will not diminish as the remnant cools. It depends only on the spinning, magnetized neutron star, not on the temperature of the gas. Because of this peculiar property, synchrotron radiation is referred to as non-thermal emission. Spinning magnetized neutron stars, also called pulsars because they emit pulses of electromagnetic radiation, are seen to slowly lose their spin over long periods of time. There is a lot of energy in the spin of such a massive object, and if it's slowing, that energy has to go somewhere. Careful study of the energy emitted by supernova remnants shows that the energy emitted by them matches the energy lost by the slowing spin of the neutron star. Therefore, astronomers conclude that late in the life of a supernova remnant, its energy comes from the neutron star itself. Examples of this kind of remnant are the Crab Nebula and the Vela supernova remnant.

Vela Nebula

Crab nebula

However, that's not always the case. If the original supernova explosion is off-center (not a perfectly expanding sphere), it can give a "kick" to the neutron star, basically acting like a rocket. The neutron star can be ejected from the explosion at very high speeds, hundreds of kilometers per second. After hundreds of years, the neutron star can actually leave the supernova remnant. In those cases, the main source of energy for the gas is gone. These supernova remnants still glow from their own heat, but they tend to be (but are not always) much fainter than pulsar-energized remnants.

By examining supernova remnants at these different energies, astronomers learn different things about them. Their ages, energy, chemical content, and much more can be determined by multi-wavelength observations. That's why NASA, ESA, and other space agencies continue to launch high-energy observatories; it's only when seen at these different energies that the Universe reveals its secrets.

TIMELINE DESCRIPTION

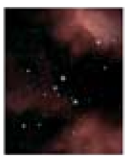
When the supernova blast wave breaks through the surface of the doomed star, it sets into motion a series of events and processes which will literally shape the fate of the expanding gas over the ensuing millennia.

The outer layers of the star explode outward due to the blast wave created when the core of the star collapses. The heat and pressure from this blast are so high that nuclear fusion can actually take place in the material. Elements up to uranium on the periodic table are created, many of which are radioactive. Isotopes of cobalt, aluminum, titanium, and nickel are all produced in the fireball. Expanding gas normally cools, but as these radioactive elements decay they produce gamma rays. The gas absorbs this radiation, heating it. After a week or two, much of the light emitted by the supernova remnant is due to this heating from radioactive decay.

As time goes on, the remnant continues to expand. During the first stage of its life, the gas in the remnant is dense enough that it is opaque; we only see the outer part of the expanding cloud. But as it expands its volume increases, so its average density drops. Eventually, like a fog clearing, the gas becomes transparent to visible light. We see deeper into the remnant, and after a few years the spinning pulsar—the collapsed core of the star— becomes visible. The gas inside the remnant is energized by the magnetic fields of the pulsar (see above). That gas is diffuse and to our eyes glows with a bluish hue. The gas in the outer parts of the remnant, however, has been compressed into thin filaments and ribbons by the shock wave, and is dominated by line emission. This gas glows mostly red and green.

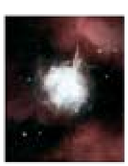
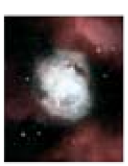
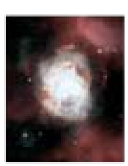
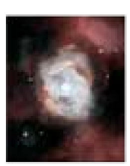
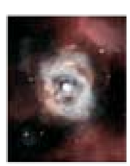
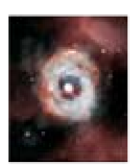
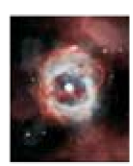
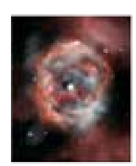
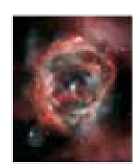
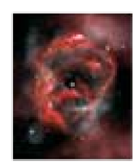
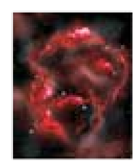
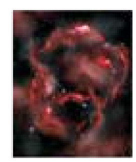
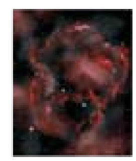
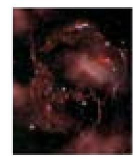
Over many thousands of years, the pulsar-driven gas from the inner part of the nebula has caught up with and merged with the outer gas. The pulsar spin has slowed, its energy given to the expanding remnant. All that's visible now are the shocked filaments, thin wisps of gas. The remnant resembles a giant spider web.

Eventually, over tens or even hundreds of thousands of years, the gas in the remnant mingles with the gas between the stars in the Galaxy. The remnant is no longer a discrete entity, but instead has merged with the interstellar medium. Stars form from such regions of gas and dust, and are thus enriched by the supernova explosion: heavy elements such as calcium, silicon, uranium, iron, and many others seed the nascent stars. These heavy elements may be necessary to form planets, and in fact the iron in our blood and the calcium in our bones were formed in the heat and fury of some ancient supernova. We owe our very existence to some long-dead star, whose remains deposited its contents into the cloud of gas and dust that eventually became the Sun, the Earth… and us.



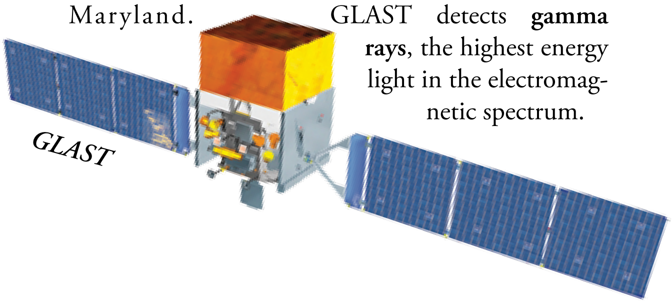




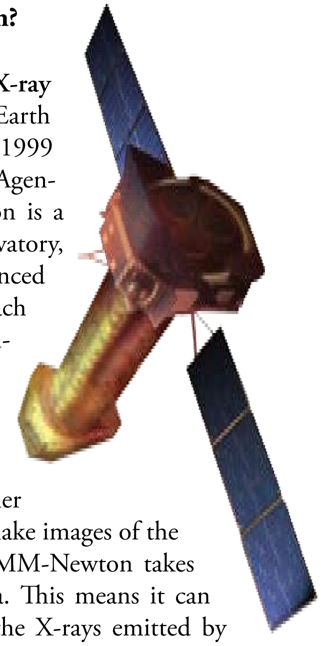















What is the Gamma-ray Large Area Space Telescope (GLAST)?

The Gamma-ray Large Area Space Telescope (GLAST) is a NASA satellite planned for launch in 2007. GLAST is part of NASA's Science Mission Directorate. Astronomical satellites like GLAST are designed to explore the structure of the Universe, examine its cycles of matter and energy, and peer into the ultimate limits of gravity: **black holes.** GLAST is being built in collaboration between NASA, the U.S. Department of Energy, France, Germany, Italy, Japan, and Sweden. The project is managed from NASA's Goddard Space Flight Center in Greenbelt, Maryland. GLAST detects **gamma rays**, the highest energy light in the electromagnetic spectrum.



What is XMM-Newton?



XMM-Newton is an **X-ray** satellite launched into Earth orbit on December 10, 1999 by the European Space Agency (ESA). XMM-Newton is a fully-functioning observatory, carrying three very advanced X-ray telescopes. They each contain 58 high-precision concentric mirrors, nested to offer the largest collecting area possible to catch X-rays. Unlike many other telescopes, which only make images of the objects they observe, XMM-Newton takes both images and spectra. This means it can measure the energy of the X-rays emitted by an astronomical object, which allows scientists to determine many of its physical characteristics including temperature, composition, and density.

This poster acompanies an educator guide which contains the following activities:

Activity 1 - Biography of a Supernova

Brief overview:
Students will write an essay describing the evolution of a supernova remnant based on pictures from the Supernova Poster.
Grades: 7 – 12

Activity 2 – Crawl of the Crab

Brief overview:
Students use two images of a supernova remnant separated in time by several decades to determine the expansion rate of the glowing gas.
Grades: 8 – 12

Activity 3 – At the Heart of a Supernova Explosion

Brief overview:
Students investigate the magnetic fields and other properties of pulsars and compare them to the Earth's magnetic field.
Grades: 8 – 12

Get the guide at *http://xmm.sonoma.edu/edu/supernova*

Credit

This poster has been developed as part of the NASA Education and Public Outreach (E/PO) Program at Sonoma State University, under the direction of Professor Lynn Cominsky.

Contributors to this education unit include Professor Lynn Cominsky, Dr. Kevin McLin, Dr. Philip Plait, Sarah Silva, and Aurore Simonnet. We would also like to acknowledge input from lots of other nice people too.

To learn more about GLAST, and XMM-Newton education and public outreach, visit:

http://glast.sonoma.edu or http://xmm.sonoma.edu