Supernova Explodes inside Computer

Expressing the inferno in mathematical terms is what the scientists at the **Max Planck Institute for Astrophysics** *in Garching are dedicated to. They simulate the explosion of a supernova.*

Optical image of the Crab Nebula, taken through the Very Large Telescope at the European Southern Observatory. High-energy particles emitted from the rapidly rotating neutron star cause the gas at the centre to radiate in a bluish light.

Photo: ESO

There are still mysteries in our enlightened world. One of them is how supernovae come into being, those spectacular stellar explosions that astronomers observe every once in a while. Now, astrophysicist Professor Wolfgang Hillebrandt and his team at the Max Planck Institute for Astrophysics are trying to solve that mystery by using numerical simulations.

The phenomenon has been known for a long time: stars that suddenly appear like flashes in the night sky and continue to shine brightly for a few months, only to dwindle away eventually. The oldest records referring to those "new stars", written by Chinese astronomers, date back to the 11th century A.D. In 1572, the Danish astronomer Tycho Brahe discovered a supernova that could be seen with the naked eye, and Johannes Kepler observed a new star appear in the year 1604.

Ever since scientists have started searching for those stellar catastrophes using automated search programmes that scan the night sky for possible changes, they have found more than 100 supernovae each year in all regions of the cosmos. While these objects usually appear to be nothing but tiny spots of light, they count among the most spectacular events in the universe. "For a short time, the luminosity of a supernova may rival that of an entire galaxy with 100 billion stars, making it sufficiently bright to be observed with large telescopes at a distance of billions of light-years", says Wolfgang Hillebrandt. Hence, the light that reaches us not only tells us about an event that happened a long time ago, but can also be used for measuring the universe.

It is only a distant light in the darkness of the night – but we are able to analyse its spectrum and observe how it changes over time. Even the best telescopes will not yield more information about a supernova. Our main problem is that light is only emitted from the star's outer layers. The events at the core remain hidden since the matter that stars are made of is opaque. "In the case of a supernova, it typically takes several years for the gas to expand far enough to become transparent", says Hillebrandt, and at that stage, those remote supernovae have frequently become so weak that they are almost impossible to observe.

Still, scientists have been successful in modelling the events that occur during the explosion of those giant balls of fire. To test these models, they use a computer to simulate the event, and later compare the "calculated explosions" to those actually observed in the sky.

By now, they have found two basic types of supernovae: one of them – which, for historical reasons, has been labelled Type Ia – emerges each time a white dwarf star is incinerated by thermonuclear reactions. The inferno of fusing atomic nuclei heats up the exploding star, creating heavy chemical elements such as iron. The formidable supernova explosion pushes the entire matter out into space in a hot cloud. Those phenomena have indeed been observed. But there also must be supernovae of a different kind, since their light shows that they are composed of different chemical elements, and after the explosion a neutron star or even a black hole is left behind in their centre. Depending on their attributes, they are categorised as Types Ib, Ic or II.

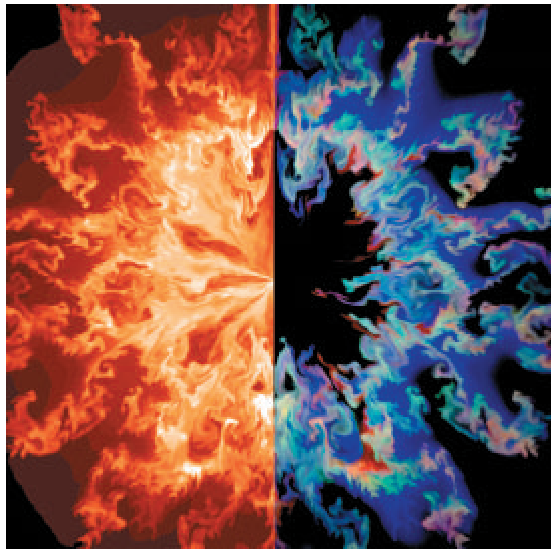
What is the essence of that other kind of supernova? For fifty years now, scientists have been thinking about that problem, designing a multitude of models that could not be tested at the time. All of that changed on February 23, 1987, when a supernova lit up in the Large Magellanic Cloud, just 170,000 light years away. This event could be linked to elaborate neutrino experiments deep beneath the Earth's surface in Italy, the US, and Japan. Down there, scientists succeeded in capturing neutrinos that were emitted simultaneously with light from the supernova. Since those tiny uncharged elementary particles travel at the speed of light, the physicists concluded that the neutrinos must also have originated in the supernova. ►

PRIZE AWARDED TO SCIENTISTS IN GOLM

Scientists at the Max Planck Institute for Gravitational Physics (Albert Einstein Institute) in Golm have designed a program that continuously monitors network quality during computing operations, measures the efficiency of calculations spread over different computers, and allocates data to supercomputers in the most efficient way. For this achievement, they have now been awarded the "Gordon Bell Prize". The award intends to acknowledge innovative techniques for increasing efficiency in computer applications.

"Ever-increasing demands on computing in basic research require ever more powerful computers", says Bernard Schutz, director at the MPI. "Hence, scientists are depending on the most efficient use of existing computing capacity. Grid computing, the networking of computers around the world in order to utilize dormant resources, is part of that effort. After the World Wide Web, that could be the next big step in Internet use. Large computing capacities could be accessible for many more people."

20 neutrinos seems to be a small amount, but it is actually a lot considering the fact that those particles very rarely collide with regular matter, making it almost impossible to detect them. "Out of a billion neutrinos that pass through the earth, only one, on average, collides with an atom of the entire globe", says Hans-Thomas Janka of the Max Planck Institute for Astrophysics in Garching. Thus, through extrapolation, the scientists arrived at the unimaginably high number of 1058 neutrinos radiating into the surrounding space during the supernova explosion. From this fact, the astrophysicists concluded that the neutrinos must be the dominant force behind this type of supernova.



Computer simulation of the explosion of a massive star, about 20 minutes after the start of the outburst. The area shown has a diameter of 4.4 million kilometres. The density of the gas is shown on the left, the distribution of chemical elements on the right.

ASTROPHYSICISTS AS SCRIPTWRITERS

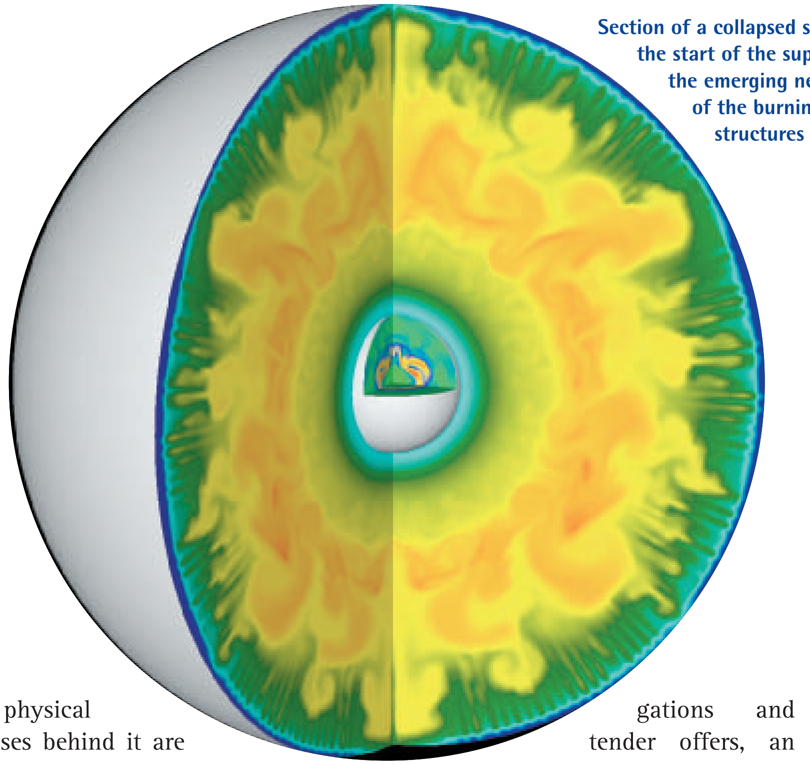
The knowledge we have obtained about the creation and progression of supernovae is one of the most fascinating areas of physical science, as it includes classical physics as well as the theory of relativity, quantum mechanics, elementary particle physics, and the description of extreme states in terms of temperature, density and pressure: nothing in this area can be measured by terrestrial standards; a situation that requires an extraordinary amount of imagination and daring on the physicists' part. During the past few years, a model has emerged which is, as Hans-Thomas Janka puts it, a "fascinating script for a supernova". Using computer simulations, that script has now been acted out, confirmed, and made visible on the screen. The interior of an old, massive star collapses under the weight of gravitational forces, and a neutron star is born. In the process, temperatures raise to about 100 billion degrees. From inside the neutron star, neutrinos, confined within a radius of a few dozen kilometres, start heating up the star's outer layer. Within a tiny fraction of a second after the collapse, conditions there are similar to the inside of a bubbling saucepan: hot matter bubbles up from below while cooler ingredients sink to the bottom, with everything seething furiously. Next, a ball of fire races outward, mixing up the elements and further heating up the outer layers.

It takes an extreme effort to simulate these events on a computer. In order to design a sufficiently exact model of the energy transport carried out by neutrinos and their interaction with the stellar medium, the equations describing the dynamics of stellar matter – which are complex enough already – have to be linked to the corresponding transport equations. Solving those equations alone occupies more than 90 percent of computing time. "Even for simulations based on the concept of the star as a symmetrical, round sphere, 10 billion computing steps are required for each step in time", says astrophysicist Markus Rampp.

On the other hand, turbulence on various length scales plays an important part in Type Ia supernovae, forcing the scientists to compute variations on scales from hundreds of kilometres down to a few millimetres. However, the direct numerical simulation of a star with a diameter of 1,000 kilometres on a millimetre scale is beyond the powers of any supercomputer. For that reason, scientists in Garching model the effects on very small scales and include them only where necessary.

Still, computing times are extremely long: for example, it takes days, even weeks, just to simulate the thermonuclear fusion "flame" that propagates outwards from a supernova. "Incidentally, similar processes occur inside the cylinder of a combustion engine, even though the physical causes behind it are completely different", says Hillebrandt. "For that reason, our calculations are very well suited to simulate and predict the combustion behaviour of hydrogen engines." Apart from computer time, there is also a tremendous demand on memory: up to two hundred gigabytes are required. Since even the Cray T3E at the Garching Computer Centre often proves to be insufficient for this task, Hillebrandt's team sometimes has to substitute the Hitachi supercomputer SR8000-F1 at the Leibniz Computer Centre of the Academy of Science in Munich.

FIGURES: MPI FOR ASTROPHYSICS



Section of a collapsed stellar iron core, about a tenth of a second after the start of the supernova explosion (Type II). The inner sphere shows the emerging neutron star, while the outer shell marks the position of the burning front at several hundred kilometres. The complex structures describe convective instabilities.

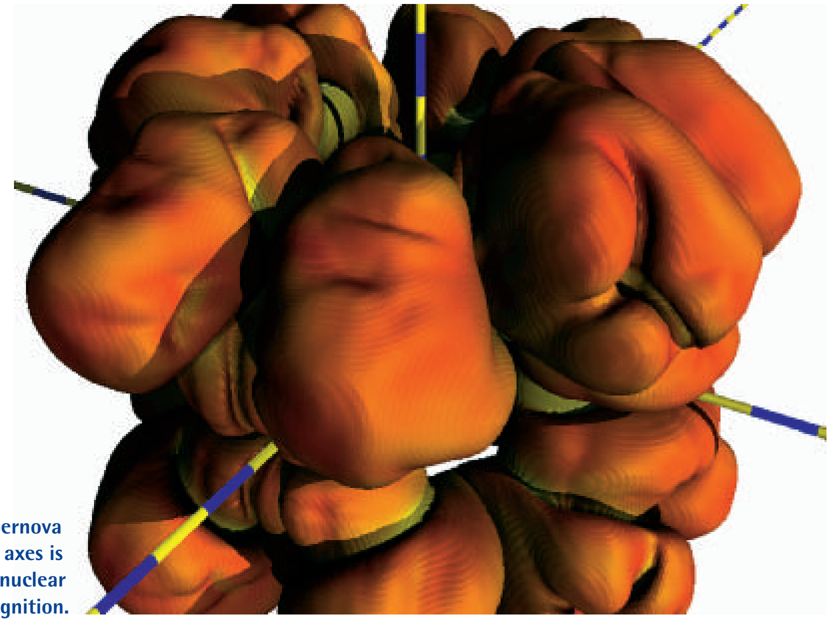
THE ACTUAL EXPLOSION FIZZLES OUT

However, it looks like the situation in Garching will improve soon. "Many institutes have been critical of the severe bottlenecks, and they have asked for the acquisition of a new computer that would be noticeably more efficient", says Hermann Lederer of the Garching Computing Centre. "After several market investigations and tender offers, an IBM Power-4 system with more than twenty nodes was finally selected." Each node of this parallel computer will have more than 32 processors and 96 gigabytes of main storage. In January 2002, the first six nodes became operational, with the rest of them to follow by the end of the year. By that time, Garching will once more have one of the world's biggest computers for civilian use.

Now, the astrophysicists can resume computing at full force – and maybe solve a problem that has almost driven them to despair. No matter how well their supernovae Type Ia simulations worked or matched their observations, those neutrino-type supernovae so far have simply refused to ignite: "The energy is just strong enough to break up the nuclei in the star's interior into free protons, neutrons, and helium nuclei", Wolfgang Hillebrandt explains, "but there is nothing left for the actual explosion."

Thus, the excitement continues: the scientists believe that a realistic simulation absolutely requires three-dimensional calculations for the physics to be described properly. However, that means accumulating 1018 computing steps for each run. Even if next-generation supercomputers were used, computing time would add up to several hundred hours, with memory requirements of up to ten gigabytes per computer node: a truly "astronomical" computing problem.

BRIGITTE RÖTHLEIN



Computer simulation of a thermonuclear supernova (Type Ia). The scale of the length unit on the axes is 100 kilometres. The figure shows the thermonuclear burning front about half a second after ignition.