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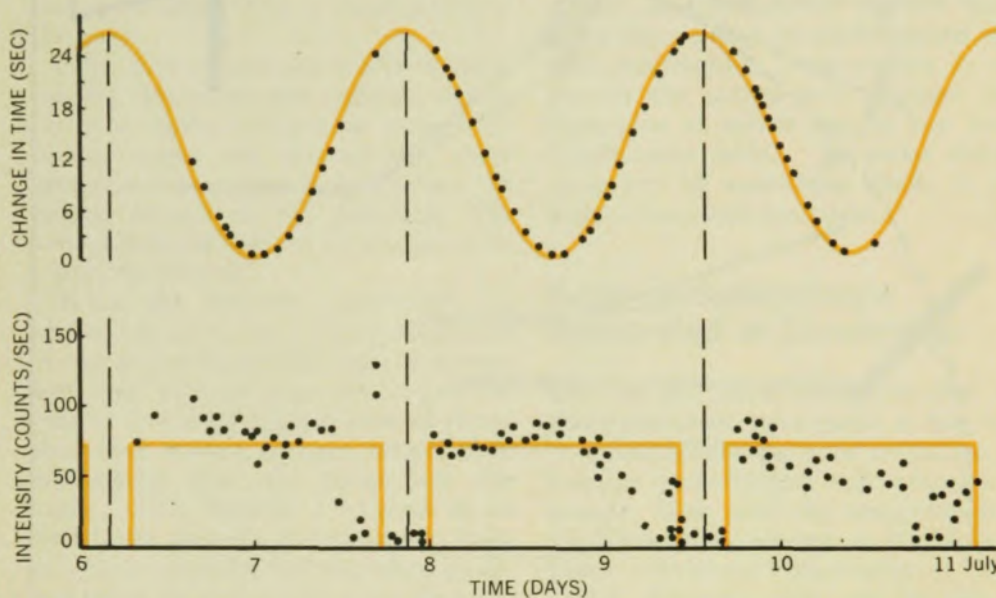
Hercules X-1: an x-ray binary system with a pulsar

A binary x-ray source called Hercules X-1 has been attracting a great deal of attention lately. It turns out to have a pulsar associated with it, thus making it possible to determine directly for the first time the mass of a neutron star. Furthermore, the pulsar has been found to be speeding up, unlike other pulsars, which usually slow down. This result was reported to the Sixth Texas Symposium on Relativistic Astrophysics (held in New York) in December by Harvey Tananbaum of American Science and Engineering.

At the same meeting Neta Bahcall (Princeton University) reported that she and her husband, John (Institute for Advanced Study), had optically identified the companion star, HZ Herculis, and its intensity varied with the same period as the x-ray intensity, 1.7 days; surprisingly, the optical signal was in phase with the x-ray signal.

One must be careful in talking about the period of Hercules X-1; it actually has three different ones: the 1.24-sec period of its pulsar or neutron star, the

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Effects of 1.7-day orbital period of Hercules X-1. Bottom diagram shows x-ray eclipses. Each dot represents a single observation with the Uhuru satellite. The space between adjacent rectangles represents an eclipse. Some low points shown within the rectangles as a high state exist because of the presence of additional gas within the binary system, according to Harvey Tananbaum. Top diagram shows delay or advance in arrival time of 1.24-sec pulses; sine wave is fitted to data. The data are Doppler shifted as the x-ray source orbits its companion; this shift causes the sinusoidal variation that is shown.

Flash x-ray technique studies crystals during shock wave

Using flash x-ray diffraction, two Livermore experimenters say they have obtained for the first time an x-ray diffraction pattern of shock-transformed material at the instant of transformation. The experiment was reported by Quintin Johnson and A. C. Mitchell (*Phys. Rev. Letters* 29, 1369, 1972).

Because one thinks of a shock wave as a violent, chaotic mess, Johnson told us, one might suspect that you could not obtain an orderly crystalline arrangement. But resistivity and pressure-volume measurements have shown that shock pressures can cause crystal-structure transformations within 100 nanosec. Until the new Livermore measurements, however, no one had been able to inspect the actual crystal structure that exists under dynamic conditions.

The experimenters used a piece of compression-annealed pyrolytic boron nitride and hit it with a shock wave

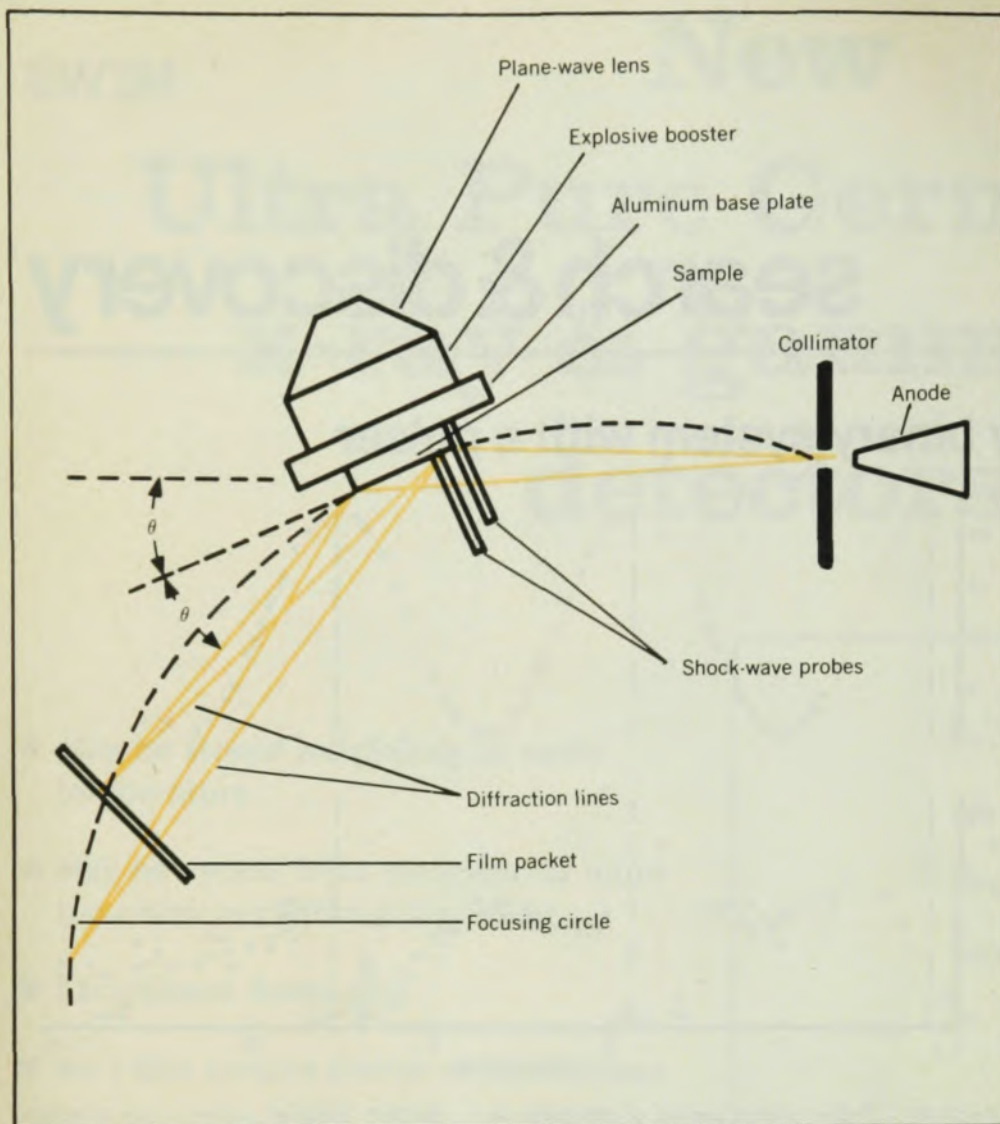
from a small explosive charge, thus subjecting it to a shock pressure of about 245 kbar. The boron nitride has a crystal structure similar to graphite. In earlier experiments, in which the sample was recovered, it had been shown that at a shock pressure of about 120 kbar, boron nitride transforms to a structure like wurtzite, which is hexagonal.

To do the flash x-ray diffraction, the Livermore workers charge a Blumlein, which is a very low-impedance capacitor, up to 50 or 60 kV and then switch the charge onto an x-ray tube. They get between 10 000 and 20 000 amps at about 80 kV. To actually do the x-ray measurements, they use copper (8 kV) or molybdenum (17 kV) radiation.

One of the major tricks of the whole experiment is to synchronize the x-ray source with the shock wave; this had to be done in terms of absolute time down to about 10 nanosec. Johnson and

Mitchell were able to time a 40-50-nanosec x-ray pulse so that maximum intensity occurred at the instant the shock wave reached the front surface of the sample. If you turn it on too early the wave will not have reached the front side of the sample; if you turn it on too late the wave will have reflected and be starting back.

The boron-nitride sample is 1.3 cm $\times$ 1.3 cm $\times$ 0.1 cm. The wave travels at a velocity of 5 mm/microsec in the 1-mm-thick direction, entering from the back side. It reaches the front side, where it sees a discontinuity and is reflected as a release wave; the pressure then drops to zero. The part of the sample actually looked at is under compression for probably about 100 nanosec. The experimenters only put their x-ray pulse on for 50 nanosec, however, because the sample absorbs x rays and you get your best look at the surface—further down you don't



Flash x-ray diffraction apparatus used at Lawrence Livermore Lab. θ is the Bragg angle.

see nearly so well with the x rays.

The experimenters photographed the sample before and during the shock wave (see photograph). They find that they have most likely produced a wurtzite structure. It can no longer be questioned, they note, that sufficient time exists for a phase transformation to occur at a shock front.

Furthermore the experimental results indicate a mechanism for the transformation. The data can be interpreted as showing that the hexagonal axis of the graphite phase becomes the [110] direction of wurtzite. This indicates the hexagon of graphite-like boron nitride deforms to the "boat" configuration rather than to the "chair" configuration.

Johnson told us that "after the shock the sample goes bye-bye. We have 100 grams of high explosive behind this

1-mm sample, and if you can find anything afterwards, you're doing very well." If you want to recover the material, you essentially put a lead brick behind the sample. The momentum of the shock is transferred to the lead, which then disappears, while the sample stays put. In such recovery experiments the sample is put in a holder with a lot of momentum traps on it. When the shock wave hits the apparatus, it flies apart, except for the special can containing the sample; this can either remains stationary or gets shot into a barrel of water or something similar. In recovery experiments with diamonds, they are always of very small particle size, say 100 Å, Johnson told us. In the new experiment, you can tell by the width of the diffraction line and the intensity that the particle size is much larger. "We have not

subjected the sample to all the reverberation and the temperature drop, etc., so at that instant we still have what amounts to a very sizable diamond. If we could only go in there and pull it out, we'd be rich. Of course it's not diamond; it's the closely related structure—wurtzite."

Recently (*JETP Letters* 16, 4, 1972) L. A. Egorov, E. V. Nitochkina and Yu. K. Orekin in the Soviet Union have reported observing diffraction from shock-compressed aluminum. This type of experiment is a prelude to the complicated phase-change study, Johnson told us. The Russian workers used a longer x-ray pulse and a semitransparent anvil over the sample. The shock wave goes through the sample and past its front surface to the anvil. The sample is lithium over aluminum; there was a microsecond time interval to look at the aluminum. Johnson says it is very complicated to interpret the Soviet results because the pressure doesn't drop to zero and you get sample motion, causing the lines to smear.

Livermore and other high-pressure laboratories have also been doing static x-ray diffraction. With this technique, Johnson says, you are limited by the strength of materials to pressures not much greater than 300 kbar. With shock-wave experiments, he says, you should be able to get 1 or 2 megabars.

Using flash x-ray diffraction to study phase transformations during shock-wave compression should yield many answers to long-standing problems of very high-pressure polymorphisms, the Livermore experimenters say. One now has a powerful tool for understanding the microscopic behavior of atoms subject to shock-wave compression. You can use the flash x-ray technique for any event that has a crystalline lifetime in the neighborhood of 1 to 100 nanosec. Not only will you be able to study shock-wave events, but probably also melting, Johnson told us. To study melting, you might subject a crystalline metal to an intense electrical pulse, heating it to the melting point. Then you might ask how long the metal really takes to melt—how long it takes for the metal to lose crystalline order.

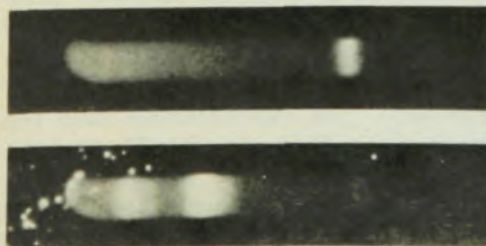
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1.7-day orbital period for the neutron star moving around the larger optical star, HZ Herculis, and a 35-day period for modulation of the intensity of the x rays.

The change in the 1.24-sec period of the pulsar is a small one indeed—over a six-month interval the American Science and Engineering group found the



Flash x-ray diffraction records of boron nitride. From left to right gives increasing values of twice the Bragg angle. Top record was obtained before shock-wave compression and shows only the 004 copper $K\beta$ line. Bottom record was taken at the instant the shock wave emerged from the front of the sample. Note that new lines appear. The small spots are shock-induced artifacts.