Ben Jonson. None are even close to the predictions of their model for Shakespeare's works. For example, in a poem by John Donne, there were 17 words that Shakespeare never used, although the prediction was for about 8 in a poem of that length.

Persi Diaconis, a statistician at Stanford who is familiar with Efron and Thisted's analysis, says it has altered his own opinion of the newly discovered poem. "I read the poem and it didn't sound anything like Shakespeare to me. I thought any sort of numerical analysis would show that the words are wrongly distributed. But now that I've seen Brad and Ron's analysis, it seems quite plausible to me that the poem could have been written by Shakespeare. I'm as convinced as I would be by any other authenticity check."

Efron stresses that their analysis cannot prove that Shakespeare wrote the poem. But, he says, he is amazed that the newly discovered poem "fits Shakespeare as well as Shakespeare fits Shakespeare." ■

GINA KOLATA

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Is Cygnus X-3 a Quark Star?

From a distance of 37,000 light years, the most luminous x-ray source in the galaxy seems to be showering the earth with a new kind of particle; could it be quark matter?

DURING a 10-day period in October 1985, at a time when the galactic x-ray source Cygnus X-3 was undergoing its most violent outburst on record, a flurry of anomalous cosmic ray events from the direction of Cygnus appeared in a proton decay detector deep in Minnesota's Soudan iron mine.

The Minnesota physicists are the first to urge caution: like the events they reported last spring, these October data are inconsistent with any known elementary particle. However, the earlier events have also survived every attempt to explain them away, and the more recent events have markedly improved the clarity of the signal. If the data are real, then the ultrarelativistic debris from Cygnus X-3 contains something totally new to particle physics.

"My gut feeling is that the signals are spurious in some way we haven't understood," says University of Wisconsin theorist Francis Halzen, who has become deeply involved in interpreting the Cygnus phenomenon. "But even if there is only a 1 in 10 chance that they are right, the implications are so important that they must be investigated."

Indeed, if the Soudan events are taken at face value, one of the first implications is that "neutron" stars such as Cygnus X-3 may not be made of neutrons at all. They may instead be spheres of degenerate quark matter.

Cygnus X-3 itself is not a particularly bright source from a terrestrial standpoint; as the name suggests, it is only the third strongest x-ray source in the constellation of Cygnus. On the other hand, it lies some 37,000 light years away, on a far edge of the galaxy where it is heavily obscured by interstellar gas and dust. Intrinsically, Cygnus X-3 is one of the two or three most luminous objects in the galaxy; it and perhaps a few other such sources seem to produce all the ultrahigh-energy cosmic rays above 100 to 1000 trillion electron volts (TeV).

Cygnus X-3 appears to be a binary system consisting of a compact object—call it a neutron star for now—pulling in a stream of gas from a more or less normal companion star; in the process the gas is heated sufficiently to produce the x-rays. The angle of the system is such that the neutron star is eclipsed once every orbit as it passes behind the larger companion. Thus, the corresponding rise and fall of the x-ray signals observed on earth gives a measure of the orbital period: 4.79 hours. However, the source is far from steady. In September 1972, Cygnus X-3 gained astronomical notoriety with an outburst that increased its radio emissions a thousandfold. Since then, smaller outbursts of varying strengths have appeared every 367 days. No one yet understands why the star flares, much less why it does so periodically. Perhaps the normal companion undergoes periodic pulsations of some kind, or perhaps there is a third body that orbits the two companions and regularly perturbs them. But whatever triggers the flares they are exceedingly violent events. During the outburst of October 1982, Ken Johnston of the Naval Research Laboratory was able to detect the shock wave using the Very Large Array near Socorro, New Mexico: it was expanding at roughly one-third the speed of light.

The most recent burst, which lasted from 3 October through 13 October 1985, came at the predicted time within a day and proved to be the largest ever. Observations were made from the ground at radio and infrared wavelengths, and from the European Space Agency's Exosat spacecraft at x-ray wavelengths. Although the astronomers are still reducing and cross-correlating their data, says Johnston, he, for one, is excited. "It's adding a whole new dimension to the model," he says.

What makes Cygnus X-3 a particle physics problem, however, is not the astrophysics but the underground data. The first indications came in 1983, when showers of muons from the general direction of Cygnus X-3 began to show up in the prototype proton decay detector operated in the Soudan mine by physicists from the University of Minnesota and the Argonne National Laboratory. The effect was small: when the Minnesota/Argonne group published its results in the spring of 1985, they only had 60 anomalous events from a 3-degree cone around Cygnus X-3 out of a total background of 1200 events. But those 60 events came with a period of precisely 4.79 hours, and stayed precisely in phase with the radio, x-ray, and infrared emissions. "It's like picking out a lighthouse on a foggy night," says Minnesota's Marvin Marshak.

What made these particular muon showers so striking, aside from their association with an object 37,000 light years away, was that they seemed to have no explanation in terms of known physics. Since muons are unstable and short-lived, they are presumably produced by some kind of primary particle from Cygnus X-3 interacting with the earth's atmosphere or with the rock around the detectors. The fact that the periodicity is detectable over a distance of 37,000 light years, however, means that all the primary particles have to be moving at virtually the same speed, the speed of light; otherwise some would lag behind the others and the signal would be washed out. The fact that the primaries still show some directionality means that they must be electrically neutral; otherwise the galactic magnetic field would have deflected and randomized them.

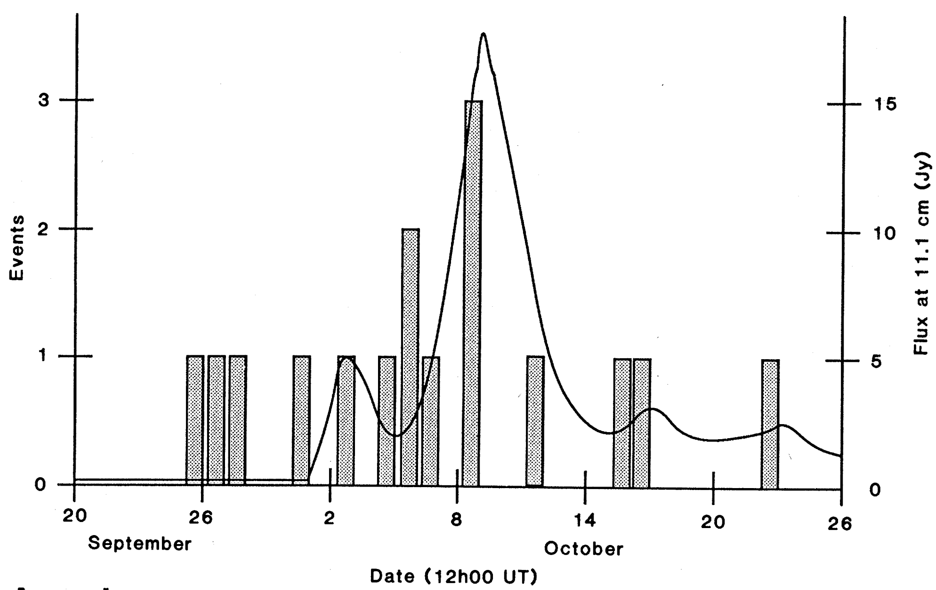
The only known particles that fit these criteria are neutrinos, photons, and ultra-high-energy neutrons. However, neutrons can be ruled out because they themselves are unstable. To make it here in time they would need an energy in excess of 10^{18} electron volts. Yet the flux of all known cosmic rays above that energy would produce only about one muon event per year in the Soudan detector.

Neutrinos can be ruled out by the zenith angle effect: the signal tends to die away as Cygnus X-3 approaches the horizon, as if the primaries were being absorbed by the atmosphere or the surrounding rock. Neutrinos are perfectly capable of traversing the whole earth and would produce an isotropic distribution of muons.

And finally, photons can be ruled out because they simply do not produce enough muons. Barring some previously unsuspected interaction mechanism, calculations show that the known flux of high-energy photons from Cygnus X-3 fails to produce enough muon showers by a factor of 300.

The physics community has understandably been skeptical of all this, especially considering the small statistics involved. On the other hand, European researchers have published similar results from the NUSEX detector under Mt. Blanc, and suggestions of a 4.79-hour signal have been found elsewhere.

Thus the significance of the October burst. Between 3 October and 13 October, the rate of anomalous muons registered in the Soudan detector went from about one event every 10 days to more than one event per day. Furthermore, when the 20 events observed during the burst were plotted relative to Cygnus X-3's 4.79-hour period, seven fell within a particular 6-minute interval—about 18 times more than expected by chance.



Anomalous muons

Plotted here is the radio flux from Cygnus X-3 as a function of time between 20 September 1985 and 26 October 1985 (solid line). Superimposed are the anomalous muon events seen in the proton decay detector at Soudan, Minnesota (grey bars). The plot shows only those events that fell within a particular 6-minute interval of Cygnus X-3's 4.79-hour period; outside that interval the muon events are much more sparse and are consistent with a random background. Within the interval, however, the events are roughly 20 times more abundant than expected by chance. Moreover, they are correlated with the radio flux.

"There's no analysis involved," says Halzen. "You can just look and see the phase bin that the events come in.

"The worry before was never really statistics but systematics," he explains. "You had to do a time sequence over years of data with a huge background, and nobody knew whether you could trust the results. But now, with the burst, my own personal opinion is that the odds have gone from about 1 in 10 to about 50–50 that the effect is real."

Unfortunately, as Marshak himself points out, no other proton decay detectors have confirmed the burst. Those that were operating at the time were probably too deep to detect it. "This isn't like an accelerator experiment," sighs Marshak. "The source isn't nice and clean. It turns on and off when it feels like it. And it doesn't care where *you* are."

Meanwhile, however, Cygnus X-3 has produced another intriguing new effect in quite a different experiment: the new cosmic ray air-shower detector atop the Haleakala volcano on the island of Maui, in Hawaii.

Operated by physicists from Purdue University and the Universities of Wisconsin and Hawaii, the detector consists of six telescopes linked in an array; the idea is to observe Cherenkov light generated when a high-energy cosmic ray enters the upper atmosphere and triggers a cascade of secondary particles. (Thus the name, "air shower.") Since the Cherenkov light follows the air shower particles within half a degree or so, the array can thus obtain a very good estimate of the direction of the original cosmic ray particle. This does mean that the event rate is low, since the shower has to be coming almost straight at the telescopes. But the payoff came on 12 October 1985, when a spectacular series of showers was seen coming from Cygnus X-3.

The showers produced a signal 4 standard deviations above the background light and lasted for a full 60 seconds, which the Haleakala group believes is highly significant: 60 seconds is very long compared to a single cosmic ray shower, which lasts about a nanosecond. But it is very short compared to typical astrophysical events. "This means that the source was totally quiescent all night," says Halzen, "then suddenly it beamed particles at us for 60 seconds, and then it totally turned off again for the rest of the night." At this point, he adds, no one is willing to guess what is going on.

Whatever their origins, the events themselves were perfectly consistent with 1-TeV gamma rays. However, relative to the 4.79-hour period of Cygnus X-3 the 60-second burst came exactly in phase with the events seen at Soudan. Indeed, Soudan had detected a muon event exactly 4.79 hours earlier on the previous cycle. (It was geographically impossible for Hawaii and Minnesota to observe Cygnus at the same time that night.)

Thus, the Haleakala burst provides strong support for the idea that last October the earth was peppered with debris from an object 37,000 light years away. "The picture we have is that the atmospheric showers are being produced by gamma rays, while an admixture of something else is producing the underground muons," says Halzen. "Or, the other possibility is that the photon interactions become anomalous at this energy. But that's as dramatic as a new particle."

The upshot of all this is that the anomalous muon events are still shaky—but much stronger than they were. So perhaps it is worthwhile taking the phenomenon at face value and seeing where it leads.

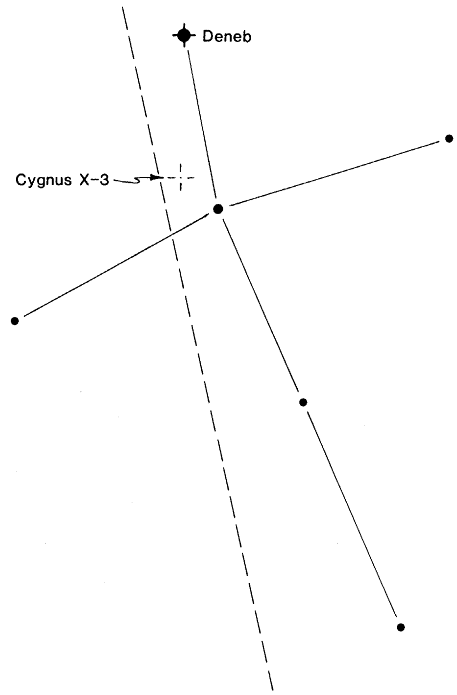
One of the most intriguing hypotheses, which has now been put forward by several groups, is that Cygnus X-3—and presumably anything else that astronomers have been calling a neutron star—is really not a 10-kilometer sphere of neutrons at all, but instead is a 10-kilometer droplet of homogeneous quark soup. "Cygnets," as the Soudan particles are sometimes called, are therefore fragments of quark matter that have been knocked loose from the surface by the same unknown process that causes the flares.

Quark matter was first proposed back in the mid-1970's, and at first glance is a pretty unlikely idea. Even in a uranium nucleus, where neutrons and protons are right on top of one another, the particles show no sign of dissolving; nature seems to be telling us that an array of 3-quark packets is much more stable than a mass of unbound quarks.

However, there is a loophole. Whereas protons and neutrons contain only two varieties of quarks, denoted "up" and "down," at least four other varieties are known to exist: "strange," "charmed," "bottom," and "top." Thus, nuclear physics only implies that protons and neutrons are the most stable state of matter in the absence of these other varieties of quark.

To see why adding new quarks might make a difference, consider what would happen if the protons and neutrons in a heavy nucleus did somehow dissociate. Since quarks obey the Pauli exclusion principle, and since only the up and down varieties are available, most of them would instantly be forced into very high energy levels in much the same way that electrons in a heavy atom such as lead or gold are forced into the highest energy orbitals. This so-called Fermi energy would be about 300 million electron volts, sufficient to tear the whole thing apart. However, suppose that some of the up and down quarks are now replaced with, say, strange quarks, as can happen through a weak interaction process analogous to beta decay. Then the strange quarks are no longer indistinguishable from the up and down quarks, and the exclusion principle no longer prevents them from falling into the lowest energy states.

There are large uncertainties in the details of this argument—among other things, strange quarks are more massive than up or down quarks—but numerical simulations suggest that a sufficient number of strange



Cygnus the swan

Also known as the Northern Cross, Cygnus is one of the familiar constellations of summer. It is marked most prominently by the bright star Deneb—the name comes from an Arabic phrase meaning "tail of the swan"—and it straddles the plane of the Milky Way, shown here as a dashed line. The position of Cygnus X-3 is indicated by a cross.

quarks might very well lower the net energy of the system and thereby make quark matter stable. Indeed, it is often called "strange matter." (It turns out that the charmed, top, and bottom quarks will not work because they are *too* massive; they would end up raising the net energy.)

Fortunately for the human race, the calculations also suggest that ordinary nuclei such as iron are exceedingly slow to undergo this conversion. The rate is governed by the weak interaction and the time required under terrestrial conditions is vastly greater than the age of the universe. However, under more extreme astrophysical conditions such as the interior of a neutron star, quark matter could become quite important. Indeed, many theorists have argued that neutron stars not only have quark matter cores, but are comprised of quark matter all the way to the surface.

This hypothesis is the basis of the quark-matter model of Cygnus X-3. Material from the normal companion is assumed to fall onto the surface of the compact star with sufficient energy to knock loose fragments of quark matter. Those fragments that are stable enough to survive—they would need to be roughly the size of a uranium nucleus—are then accelerated outward to relativistic velocities by the quark star's magnetic field, and are scattered throughout the galaxy. Indeed, considering that the Milky Way is 10 to 15 billion years old and contains perhaps a billion "neutron" stars of various ages, it seems reasonable to suppose that quark matter fragments might be fairly common in the galaxy. And in fact, certain rare cosmic ray events, including the so-called "Centauro" events seen from the Andes in the 1970's, are characterized by a primary particle that penetrates surprisingly deep into the atmosphere and then dissociates into a surprisingly rich spray of hadrons; it is at least conceivable that a fragment of quark matter would behave in exactly this fashion.

However, these fragments themselves are almost certainly not the cygnet particles producing the Soudan events. Since they are positively charged they would be deflected by the galaxy's magnetic field, whereas the cygnets appear to travel in a straight line. On the other hand, when the nuggets are flung outward from the quark star many of them would pass through the atmosphere of the normal companion. There they would be broken up into lighter fragments, some of which would be neutral, and some of which would presumably make it to Soudan.

As it happens, particle theory supplies a natural candidate: the di-lambda, or H particle. First proposed by MIT's Robert Jaffe in 1977, the hypothetical H is a tightly bound state of six quarks: two up, two down, two strange. (The "di-lambda" name refers to the fact that it has the quantum numbers of two conventional lambda particles.) Calculations suggest that the H would be neutral, that it would have a mass about twice that of the proton, and would at least be long-lived, if not stable. Thus it could make it from Cygnus X-3 to Minnesota. Furthermore, upon interaction with the atmosphere or rock above the detector the H would produce an enhanced number of muons. Thus it could explain the anomalous muon events.

Admittedly, this scenario is far from proved. It relies upon a long chain of hypotheses to explain an effect that might not even be real. However, to the extent one takes the Soudan data seriously, one also has to take quark matter seriously. In particular, the Cygnus X-3 puzzle gives renewed impetus to the search for H particle in particle accelerators, and to the attempts to create and study quark matter in relativistic heavy ion collisions. ■ **M. Mitchell Waldrop**

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