search & discovery

Sudden outburst in radio emission from Cygnus X-3

On the night of Saturday, 2 September, Philip Gregory (University of Toronto) recorded at a frequency of 10.5 GHz what Gregory calls "the most impressive outburst ever witnessed by radio astronomers." The event was in an x-ray source, Cygnus X-3, which is in our own galaxy, and its flux density in the radio had increased by a factor of 2000 over the level recorded two days earlier at the National Radio Astronomy Observatory by Robert Hjellming and Bruce Balick. Subsequent outbursts occurred later in September. These observations and a host of others are reported in a special issue of *Nature Physical Science* (**239**, 113–136, 1972), which contains 21 papers on Cygnus X-3.

The source had been discovered in a rocket flight in 1966 by Riccardo Giacconi and his collaborators, who found it interesting because it had a marked deficiency at low energy; this implied that the source was embedded in a dense cloud of gas. In 1971 the x-ray satellite, Uhuru, obtained a better position for the source. A few months ago the NRAO group started looking at Cygnus X-3. They found it varied by factors of two or three in a few hours with a mean flux density of 0.1 flux units (1 flux unit $= 10^{-26}$ watts/m^{2}Hz). But by 31 August the intensity had dropped to 0.01 flux units, both at 8085 and 2695 MHz.

Outbursts. Two days later the NRAO and Canadian groups were planning to do simultaneous observations on Algol. An hour and a half before Algol rose Gregory decided to see what Cygnus X-3 was doing, as had been the custom of his group during the previous month. (Members of the Canadian group involved in radio studies of x-ray stars and peculiar optical stars are Philipp Kronberg and Ernest Sequist of the University of Toronto, Victor Hughes, Andrew Woodsworth, Melvin Viner and Donald Retallack of Queen's University, Kingston, Ontario.) Using the Algonquin Radio Observatory 46-meter telescope Gregory recorded a flux density of 21 flux units at 10 522 MHz. When he first picked up the source it was so strong the equipment saturated. After turning down the gain, the equipment was still saturated; so he turned it down again.

After a hurried call to NRAO, Hjellming and Balick there confirmed that Cygnus X-3 was putting out approximately 20 flux units. The two groups then decided to alert radio astronomers throughout the world about their unique finding. By morning four other observatories had confirmed the flux value. By the next day, Hjellming says, "I think it's fair to say every radio observatory we reached was observing it."

At first the source looked like an example of the spectrum from a thermal source with a temperature of about 10^7K, Gregory says. But it soon showed behavior characteristic of a nonthermal source. Furthermore the Cana-

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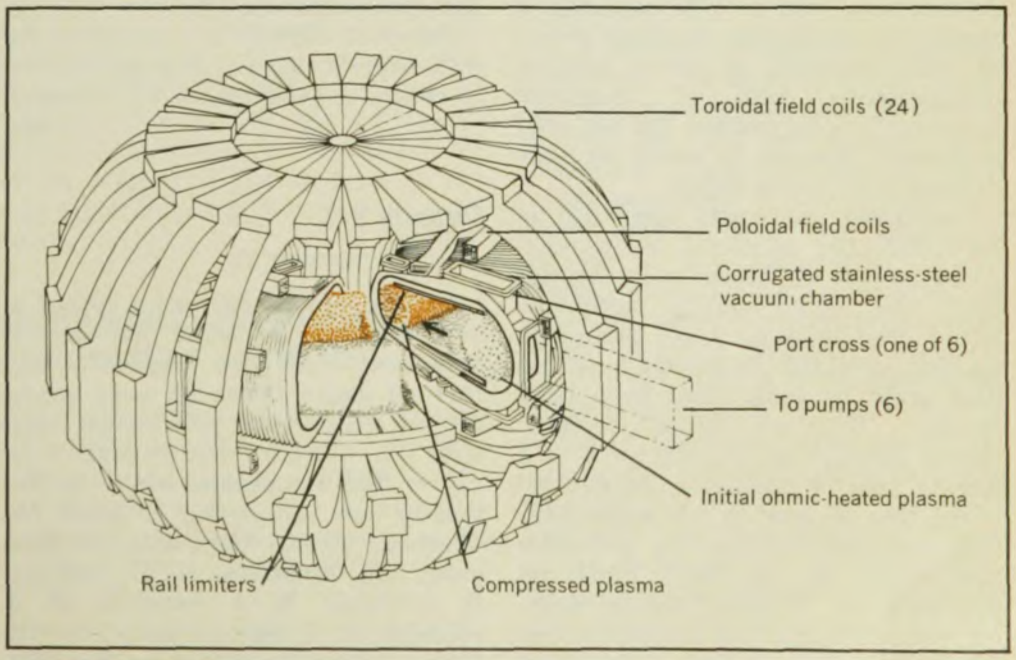
Princeton tokamak exceeds supposed density limit

A novel variation on the Russian tokamak has dispelled some of the reverence for traditional tokamak technology while achieving a modest advancement of plasma parameters. The experiment, done with the Adiabatic Toroidal Compressor (ATC) at Princeton, eliminates the copper "stabilizing shell" surrounding the plasma, which was believed to play a vital role in assuring magnetohydrodynamic stability. Furthermore it shows that heating by compression can take place in a tokamak plasma, and it indicates that there is no limit to the density that can be reached in a stable tokamak plasma. Results were reported at the November meeting of the APS Plasma Physics Division in Monterey, California and in the 27 November issue of *Physical Review Letters* (**29**, 1495, 1972).

Tokamaks first achieved great prominence in 1969 with results reported by Lev Artsimovich, who used the T-3 device at the Kurchatov Institute in Mos-



Adiabatic Toroidal Compressor. The air-core transformer induces plasma current, which heats electrons. Then plasma torus is compressed by a pulsed vertical magnetic field. Major radius contracts from 88 to 38 cm, and electron temperature rises to 2.5 kV. The peak electron density is about twice as high as in previous tokamak experiments.

cow. Subsequently several specialized tokamak devices were funded by the AEC and are coming into operation around the US. In a conventional tokamak a strong toroidal magnetic field is set up by external coils. Then a toroidally directed current is induced in a plasma torus by a large iron-core transformer; this plasma current generates a magnetic-field component that completes the magnetic bottle. Ohmic heating of the plasma is provided by the current.

In the Princeton ATC, an air-core rather than an iron-core transformer induces a plasma current, which heats the electrons to about 1 kV and the ions to about 200 eV. Then the plasma torus is compressed in major radius by a pulsed vertical magnetic field (see figure). The major radius contracts from 88 cm to 38 cm, and the temperature rises to 2.5 kV for the electrons; ion temperatures are about 600 eV. The peak electron density in the compressed state is about twice as high as in previous tokamak experiments with deuterium plasmas. Some people had believed there was a "high-density limit" below 10^{14} cm^{-3}; the Princeton experiment has exceeded this value.

Harold Furth, who together with Shoichi Yoshikawa developed the theory of adiabatic compression, told us that the ATC stability without the copper shell is as good as that of the Kurchatov T-3 or the Princeton ST, which do use such a shell. By using an air-core transformer and later pushing the plasma into the region initially occupied by the transformer flux, he said, the ATC is able to achieve a much greater radial compression factor than one could obtain in a conventional tokamak. A different idea of varying the plasma major radius is due to Artsimovich, who in 1969 proposed a method for oscillating the major radius at high frequency to create internal dissipation—a form of "magnetic pumping." This method has not been attempted because it would be very difficult to do, Furth noted.

Yoshikawa and Furth concluded in 1970 that the adiabatic compression could be just the second-stage booster that the ohmic-heating technique would need to bring a DT plasma to ignition, provided the plasma major radius could be compressed by a large factor. "Whether fusion research should actually go by this route to a toroidal reactor remains to be decided—but here at least is one experimentally demonstrated heating technique that might do the job," Furth remarked to us. A second heating method, which is being tried initially on Oak Ridge's tokamak, Ormak, is to inject high-current energetic neutral beams. Princeton believes it may be particularly advantageous to combine this kind of injection with compression; this will be studied soon in ATC.

The most important question is, of course, whether the present favorable plasma confinement and scaling will hold up in much larger tokamak experiments. To investigate this question is the principal objective of the Princeton Large Torus (PLT), a new device now in the early stage of fabrication. It is designed to push the ohmic heating technique pretty much to its limit: The plasma is expected to reach 2–3 keV for both electrons and ions at densities of 10^{14} cm^{-3}. Plasma lifetime should be about 0.3 second.

PLT is a large-bore toroidal confinement device of considerable flexibility, but basically a tokamak. That is, the very large current (up to 1.6 megamperes) to be induced in the plasma column is used both for heating and for providing the required poloidal magnetic field for confinement.

The toroidal field coils are centered on a major radius of 140 cm, have a 160-cm-diameter bore and produce a field on axis of 50 kG. The plasma minor diameter is 90 cm. As in ATC there is no copper shell or iron core; equilibrium for the plasma column is provided by specially shaped and programmed transverse fields.

The first plasmas from PLT are scheduled for the beginning of 1976, and the estimated total cost is slightly under $13 million.

Furth told us that the ATC will probably continue to hold the high-density record until the next generation of bigger machines comes into operation—PLT for Princeton and T-10 for the Kurchatov group, which is expected to operate about 1975. T-10 will be roughly the same size as PLT but will have a copper shell and an iron core, as does the T-3.

Robert A. Ellis Jr is in charge of the ATC experiment, and Donald Grove is in charge of building the PLT device.

—GBL

Cygnus X-3

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dian group found the radio output at 10.5 GHz to be about 4% linearly polarized, which also suggests a nonthermal source (although some groups did not detect linear polarization larger than 1%). The flux density began a decay at high frequencies while the flux density was still rising at lower frequencies. At 408 MHz, a Jodrell Bank group (B. Anderson, R. G. Conway, R. J. Davis, R. J. Peckham, P. J. Richards, R. E. Spencer and P. N. Wilkinson) found the maximum flux density to occur four days after the maximum found by the Canadians.

On 19 September Hjellming and Balick found a sudden increase by two orders of magnitude above the mean pre-outburst level of 0.06 flux units. As of the beginning of December Cygnus X-3 had produced four outbursts above 10 flux units.

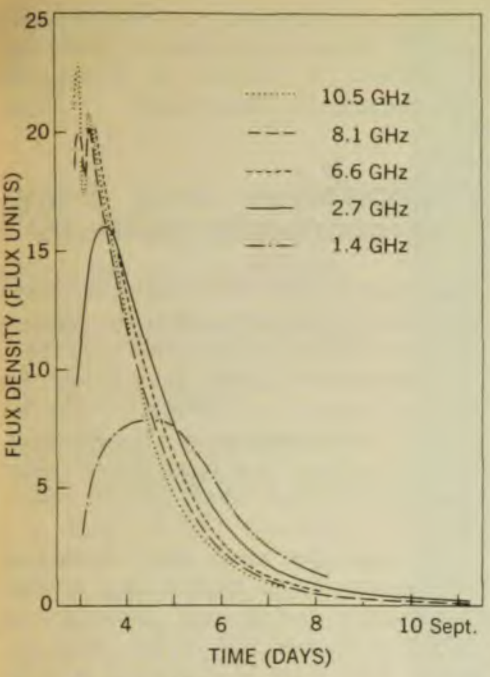
When the first outburst was found, x-ray experimenters were notified, and it was generally believed that a corresponding x-ray outburst would be found. None was forthcoming. Uhuru had been scanning the galactic plane (which contains Cygnus X-3) since 19 August, and it found no outburst from that date until 9 September, when it was reoriented to look at the pulsing x-ray source, Hercules X-1. An interesting thing was uncovered in May by Uhuru, however, namely that Cygnus X-3 had an intensity variation with a period of 4.80 hours. The Uhuru observers (D. R. Parsignault, Herbert Gursky, E. M. Kellogg, T. Matilsky, S. Murray, E. Schreier, H. Tananbaum and Giacconi of American Science and Engineering and A. C. Brinkman of Utrecht) suggest that Cygnus X-3 may, by analogy with several other binary x-ray sources observed by Uhuru, be a binary system with the intensity variations caused by eclipses. Giacconi remarked to us that the study of x-ray sources at other wavelengths reveals significant behavior. He notes that the radio output is a small fraction of the energy in the x rays, and the physical dimensions are much different in x rays than radio, making it possible that the two sources may not be related.

A search for an x-ray outburst was also made by the fourth Orbiting Astronomical Observatory, Copernicus and P. W. Sandford and F. H. Hawkins (Mullard Space Science Laboratory) found no evidence for an outburst, nor did a group using the Vela 5B spacecraft (J. P. Conner and W. D. Evans of Los Alamos and D. E. Mook of Dartmouth College) find any outburst.

No optical counterpart was found either, in a search with the Palomar 48-inch telescope made by J. A. Westphal, J. Kristian, J. P. Huchra, S. A. Shectman and R. J. Brucato (Hale Observatories).

In the infrared, however, the story was different. Searching for infrared emission at the radio position, E. E. Becklin, Kristian, G. Neugebauer and C. W. Wynn-Williams (Hale Observatories), who used the Hale 200-inch telescope, found an infrared source in the right spot.

The best distance estimate, according to Gregory, is that made by a group at the Meudon Observatory in Paris (Robert Lauqué, James Lequeux and Nguyen-Quang-Rieu). By measuring hydrogen-line absorption in front of the radio counterpart of Cygnus X-3, they determine the distance to be 8–11 kiloparsec. Such a distance would



Flux density of Cygnus X-3 as a function of time for five different frequencies.

put Cygnus X-3 behind a large amount of interstellar dust, which could explain why it has not been detected optically, Gregory remarks.

Theory. What caused the peculiar behavior of Cygnus X-3? The Canadian and NRAO groups say that it is caused by an expanding cloud of relativistic electrons. In their picture the radio emission comes from synchrotron radiation produced by the interation of the relativistic electrons with the magnetic field. Hjellming told us that the radio emission agrees well with this picture—the power law, the polarization, and the way the frequency evolves as a function of time agree well with simple theories of what happens when you have initial injection of cosmic-ray electrons with a relatively flat energy spectrum. The first outburst, in particular, fits the theory nicely.

Hugh D. Aller (University of Michigan) and William A. Dent (University of Massachusetts) think the Cygnus X-3 outburst looks like solar centimeter-wavelength bursts. They suggest that the radio emission is produced by synchrotron radiation, but they say that the exponential decay of the flux density comes from bremsstrahlung caused by Coulomb collisions between the relativistic particles and an ambient thermal plasma.

Speaking at the Sixth Texas Symposium on Relativistic Astrophysics in December, Remo Ruffini (Princeton) said that Cygnus X-3 is a black hole. He and Robert W. Leach (Princeton) argue that all x-ray sources can be separated into pulsating sources, which are neutron stars, and nonpulsating sources, most of which are black holes. (By pulsations one means sharp, well-defined and regular pulses much like the optical and radio signals from pulsars.) Ruffini and Clifford Rhoades (now at Kirtland Air Force Base) had shown that a neutron star can never have a mass larger than 3.2 solar masses if you don't want to violate causality or general relativity. Black holes are more massive than neutron stars and are always axially symmetric, unlike neutron stars. Thus it appears extremely unlikely that one can obtain long-lasting periodic phenomena from black holes; rather they might emit short bursts distributed randomly.

Because x-ray binaries are so common, Ruffini told us, we can now determine limits on the masses of many neutron stars and black holes with a precision of two or three decimal places—from the orbital period and the velocity (from the Doppler shift) of the x-ray source. The mass can be determined making various assumptions on the inclination of the binary system. This ability to measure masses of collapsed objects is the most important new factor in distinguishing between black holes and neutron stars, he feels.

For Cygnus X-1 Ruffini and Leach obtain a mass of eight solar masses. Because of its mass and the fact that it doesn't pulsate, they conclude that it is a black hole. Cygnus X-3, Ruffini explains, must be in the same family because it is nonpulsating and there is evidence for a binary period of 4.8 hours. He argues that it is a binary which, because of its period has to be extremely massive—or else the masses would be very close together and the system would have a very short lifetime, making it highly improbable that one would observe it. He therefore concludes that Cygnus X-3 is a black hole.

The Princeton work does not disagree with a synchrotron model, which refers to the shell, whereas the Princeton model talks about the collapsed object itself, Ruffini explained. Work related to the Princeton effort has been done by R. A. Sunyaev (Institute for Applied Mathematics in Moscow), who has done a detailed analysis of the structure of the disk accreting material around an x-ray source. —GBL

Multihadron production greater than expected

The cross section for the annihilation of an electron and a positron into hadrons is much higher than many had expected, according to new experiments performed with the electron–positron colliding beam devices at the Cambridge Electron Accelerator and at Adone in Frascati, Italy. Although the error bars are large, the multihadron production cross section is, for example, much higher than a simple quark model would predict.

At the recent "Rochester" conference (held at the University of Chicago and the National Accelerator Laboratory) Corrado Mencuccini reported on Frascati measurements with a total center-of-mass energy between 1.2 and 3.0 GeV. These were done by the "$\gamma\gamma$" group and the "$\mu\pi$" group. They find that the multihadron production cross section is two to three times as large as the cross section for muon pair production. Two years ago, shortly after Adone first went into operation, preliminary measurements at center-of-mass energies of 1.5 to 2.2 GeV had indicated a multihadron production cross section of one to two times the muon pair production. In the future, Adone experimenters want to modify their apparatus to better analyze the abundant multihadron production they have found. Multihadron results from two other groups were reported to the conference by Vittorio Silvestrini; these were from the "boson" group and the Bologna–CERN–Frascati group.

The Frascati experimenters also find evidence for a peak in the multihadron cross section at a total energy of 1.6 GeV that suggests a resonance behavior that can be interpreted as a ρ' meson which decays into 4π; this particle would have spin one and negative parity, similar to the ρ meson, which has a lower mass. Earlier evidence for a ρ' has been reported from photoproduction experiments at DESY and by Robert Mozley and his collaborators at SLAC.

Also at the Rochester conference CEA experimenters reported on multihadron production at a center-of-mass energy of 4 GeV. Their preliminary analysis of the data shows the ratio of the multihadron production cross section to the two-muon production cross section is within the following limits: 2.4 and 6.0.

It is difficult to make a general statement about the behavior of the multihadron production as a function of energy from the CEA and Frascati data. Theoretical predictions are all made for the asymptotic region—a place that always appears to be just beyond the horizon of the high-energy experiments. Many people are surprised at how high the cross section is compared to the "pointlike" muon-pair cross section. In asymptopia, if you have either pointlike particles or partons inside the proton (if you want to use parton language), or if you have canonical dimensions (if you want to use light-cone language), then the multihadron cross section should go as a constant over s, the square of the collision energy. From CEA and Frascati data one could draw a curve that goes as $1/s$ or a curve that is a constant independent of the collision energy.

What one can say is that the multi-