gram network in 1976. But they have been unable to reach a final agreement on what their $450-million telecommunication program should be. The objective is still the launching of a 750-kilogram satellite in 1980, but should the predecessor of this spacecraft be a 200-, a 350-, or a 500-kilogram satellite? Should it be derived from Symphonie, from the Italian telecommunication Sirio, or from the British paper study of still another satellite? As for the aeronautical satellite Aerosat, which is to be developed in cooperation with the United States, ESRO is still negotiating with the Federal Aviation Administration (FAA) and the Federal Communications Commission and trying to find an American industrial partner willing to share half of the cost, after two previous agreements with NASA and the FAA were vetoed by the Office of Telecommunication Policy in the White House.

At odds with itself, Europe is no happier in its relationship with the United States. The Aerosat affair proved very disappointing, as did the successive post-Apollo proposals; NASA offered Europe participation first in the shuttle, then in the tug, and finally only in the sortie module.

(As it stands now, ESRO at least has its foot in the hatch in the sortie module project. The module—Europeans call it a "space lab"—would fit into the payload bay of the space shuttle and remain there while the shuttle was in orbit. The module would have a life support system and accommodate scientists and their experiments for several weeks. Recently, Britain and the Netherlands have agreed to join in studies designed to come up with refined estimates of the project's costs. Belgium, Italy, Spain, and West Germany have already indicated they will participate in the module program unless costs are excessive. Results of the study, expected in August, will determine whether ESRO will go on to build the module and, if so, which nations will participate.)

Today, it can be seriously asked whether Europe and the United States will ever reach an agreement on the post-Apollo program. Europe may be reluctant to pour money into the sortie module program if NASA develops its own simultaneously. On the other hand, now that NASA has support of the Department of Defense for the post-Apollo program, it no longer has such a strong need for European assistance.

Europe's new space program was adopted without enthusiasm and amidst the conflicting interests of each nation. No one at the space conference was able to set sensible objectives, establish what the program should do for Europe, or decide what role national programs should play. Will any program born amidst so much dissension and compromise become a source of happiness to its progenitors? And yet, with national and European programs combined, Europe has so far launched 26 satellites and acquired an industrial competence which can easily provide a firm basis for more ambitious projects.—DOMINIQUE VERGUÈSE

RESEARCH NEWS

X-ray Astronomy (II): A New Breed of Pulsars

Radio pulsars were born in supernova explosions that blew out great clouds of gas into space, and then started producing enormous streams of very fast electrons and probably cosmic rays too. Or at least that is the way most astronomers picture them. Sixty or 70 radio pulsars have been discovered, and the fastest pulsar, NP 0532 in the Crab Nebula, radiates more than 100,000 times the energy of the sun. Where does all that energy come from? Thoughts that were just speculations a few years ago are almost certainties now. The Crab pulsar is a neutron star spinning around 30 times per second, and its great luminosity is sustained because the energy of rotation is continually being converted into emissions of radiation and fast particles. After 4 years of observation, astronomers now know that the pulses of the Crab pulsar are not exactly constant. Although the slowing is almost imperceptible, the pause between pulses is growing longer by 13.5 microseconds every year. The energy lost as the pulsar spins more slowly can be calculated simply, and it agrees remarkably well with the energy radiated into space.

But as a result of experiments with x-ray satellites during the last 2 years, a new type of pulsar has been found that does not emit any radio signals. The new objects might be called x-ray pulsars. So far only two such objects have been identified, but the characteristics of the x-ray pulsars are so well-defined and so different from the characteristics of radio pulsars that there is great hope for new knowledge of the underlying phenomenon. One scientist has called the x-ray pulsar an example of a neutron star in a controlled environment, because the x-ray pulsar exists in a binary system. Thus it has been possible in one case to measure the neutron star's mass (*Science*, 23 February 1973). Perhaps an even more important measurement of the x-ray pulsar has already been made, however. After clocking the period of two x-ray pulsars for almost a year, astronomers have found that they are rotating slightly faster than they did when first discovered. This almost certainly means that the x-ray pulsar is gaining energy rather than losing it, and thus scientists are forced to construct very different sorts of models for the dynamics of x-ray pulsars than for their radio counterparts.

X-ray pulsars are not the only unusual astronomical objects that have been discovered with the new telescopes, carried above the earth's atmosphere by the satellites Small Astronomy Satellite-A (named UHURU) and the seventh Orbiting Solar Observatory (OSO-7). With UHURU at least 125 sources of x-rays have now been discovered (Fig. 1). About 80 of these are found in directions within 20 degrees of the plane of our galaxy, and are thought to be located in the galaxy. Among the galactic sources, a whole menagerie of different types is found. Some of the strongest and most regular galactic sources will be discussed in this article, and the source which many scientists postulate might be a black hole will be discussed in a third article of this series. The extra-galactic objects mapped by UHURU will not be discussed, although many interesting objects outside the Milky Way appear to emit x-rays, including large clusters of galaxies, quasi-stellar objects, and Seyfert galaxies.

Very few of the sources mapped with UHURU have been studied in detail, largely because the data from UHURU and OSO-7 have swamped the principal investigators in those experiments with information. Relatively few astronomers have been able to participate in analysis of data from the satellites, largely because the funding for data analysis has been rather limited. But the objects that have been studied include binary systems, irregular sources, and nova-like sources, in addition to the x-ray pulsars.

A source that appears to have unusual patterns of radio emissions and x-ray emissions is Cygnus X-3, the object that was highly publicized when radio astronomers observed tremendous outbursts from it starting on 2 September 1972. From the x-ray observations with UHURU, astronomers have found that the source has a 4.8-hour period. This is much longer than the period of rotation of the x-ray pulsars and much shorter than the period of eclipse of other x-ray binaries. According to Jeremiah Ostriker of Princeton University, Princeton, New Jersey, it is very difficult to imagine a small star orbiting about an ordinary massive star with a period as short as 4.8 hours, so this must be a type of object different from other x-ray binaries. Radio astronomers have postulated that the source of outbursts was an expanding cloud of electrons moving at nearly the speed of light. But no change in the x-ray emissions occurred during the radio outbursts. Some scientists have wondered whether the radio and x-ray sources are really the same. So, although the explanation of the radio source may not contradict the x-ray information, it hasn't resolved the puzzle about the basic character of the system.

The brightest x-ray source in the sky, Scorpius X-1, does not seem to have any regular features at all, even though quiescent periods, active periods, and flares recur at different times. Both optical and radio counterparts to this source are known, but according to Claude Canizares of the Massachusetts Institute of Technology, Cambridge, no definite correlations have been found among the flares observed at three different wavelengths, although the x-ray and optical variations may be similar. Perhaps if Scorpius X-1 were faint few scientists would want to explain it, but the mystery of such a bright object accessible to attack with so many experimental techniques seems to have frustrated many astronomers.

The first star-sized source of x-rays to be found in another galaxy is an object in the Small Magellanic Cloud (SMC X-1). It is in a binary system with a 3.89-day period. William Liller at Harvard University, Cambridge, Massachusetts, has recently reported the identification of an optical counterpart with the same period—a massive BO star. Because the distance to the Small Magellanic Cloud, a galaxy near our own galaxy, is known, the absolute luminosity of the x-ray source can be calculated. The value obtained is surprisingly large, so large in fact that the star may be near a theoretical limit—called the Eddington limit—where the force of gravity pulling in particles is offset by the pressure of radiation going out. Reference to this limit is important because the capture and acceleration of particles by the gravitational field of the star is thought to be the source of energy for the x-ray pulsars.

The two sources that seem to be verified examples of x-ray pulsars, Hercules X-1 and Centaurus X-3, are perhaps understood better than any others. They are thought to be neutron stars with about one solar mass, orbiting about more massive stars in orbits so tight that the two stars almost graze each other. An indication of the closeness is that the x-ray eclipse lasts for about one-quarter of the orbit for Centaurus X-3 and about one-seventh the orbit for Hercules X-1. Both x-ray pulsars are speeding up. The 1.2-second pulsations of Hercules X-1 have become 4.5 μsec closer together in the course of 6 months of observation by the scientists at American Science and Engineering Com-

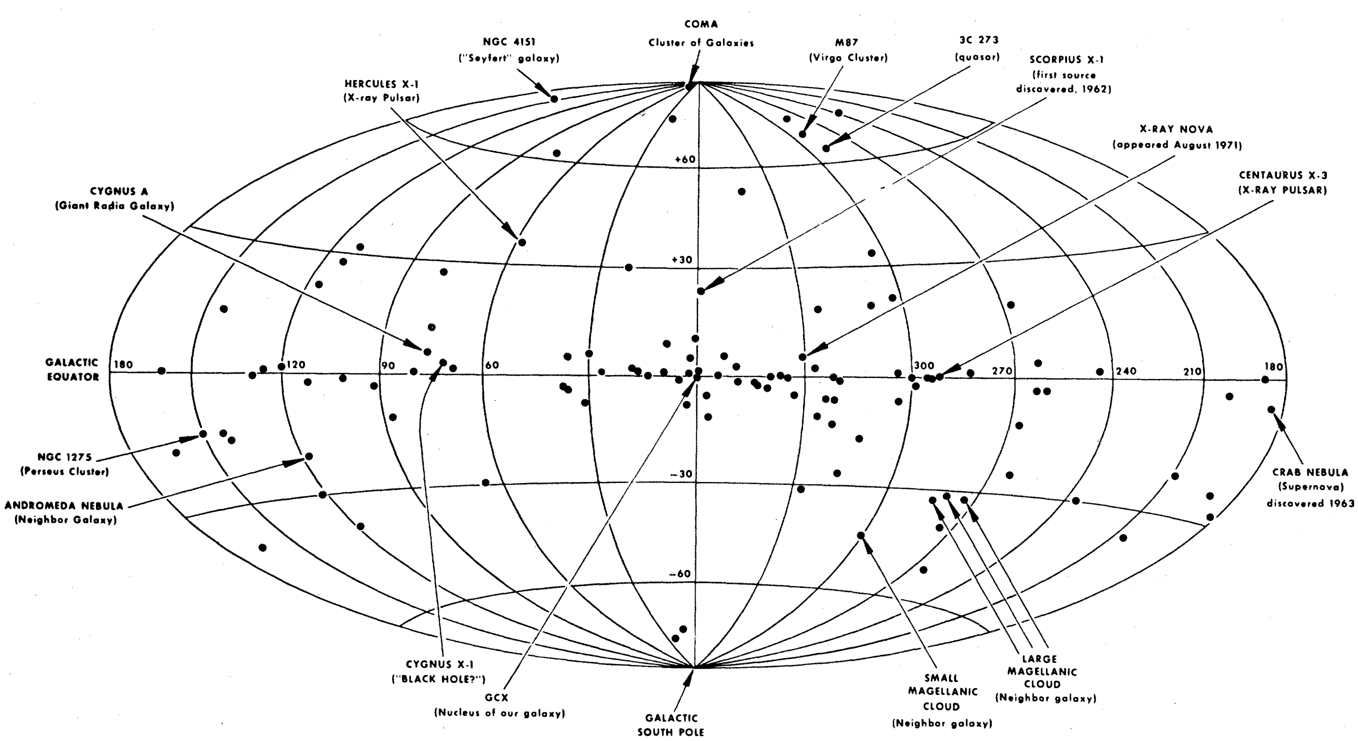

Fig. 1. A map of x-ray sources discovered with the satellite UHURU. The equator corresponds to the plane of the galaxy.

pany, Cambridge, Massachusetts, and the period of the pulses from Centaurus X-3 has decreased 200 μsec during 6 months.

If a neutron star is not slowing down, what source of energy is producing all the radiation observed from the x-ray pulsars? Because neutron stars are expected to be very small and very dense (*Science*, 19 March 1971), the gravitational energy released by matter falling on the surface would be even greater than the nuclear energy released if the same amount of matter underwent fusion. For a star such as the sun, gravitational energy is relatively unimportant, but for a neutron star with the mass of the sun contracted to a diameter of 10 kilometers, the gravitational energy is far greater than the nuclear energy. So the source of energy to produce the x-ray fluxes that are observed in Hercules and Centaurus is probably accretion of gas from the massive star that the neutron star is orbiting. The x-ray emissions would be caused when the gas hit the surface of the neutron star after being accelerated to about half the speed of light by the gravitational field.

If accretion of matter is the source of energy for x-ray pulsars, rotation of the neutron star is still necessary to provide the "clock" that makes the pulses so regular. The magnetic field of a neutron star, as understood from radio pulsars, is far stronger than the field of the earth (10^{12} gauss compared to 1 gauss). If the poles of the magnetic field were inclined off the axis of rotation, periodic variations in the x-ray luminosities might be observed as the field channeled very fast particles onto certain parts of the star's surface. As the poles rotated into view and out again, x-ray pulses would be observed. The effect would be somewhat analogous to the way particles are funneled into the magnetic poles of the earth to produce auroral displays.

Very little detailed study has been made of what would happen near the surface of a neutron star, but there seem to be two schools of thought to explain in more general terms how mass is transferred from one star to the other. One hypothesis is that the more massive star increases in size until it extends out as far as the point of gravitational equipotential for the two-star system. It is then said to fill its Roche lobe—a sort of invisible sac defined by the gravitational forces. When matter from the expanding star reaches the equipotential point, gravitational forces from the neutron star can pull it off the massive star. Models for gravitational transfer have been proposed for the source Hercules X-1 by James Pringle and Martin Rees of Cambridge University, Cambridge, England, and by David Pines and Fred Lamb at the University of Illinois, Urbana-Champaigne. The mass pulled into the vicinity of the neutron star would form a rapidly rotating disk, lose angular momentum, and fall inward to reach the surface.

The other school of thought, proposed by Kris Davidson and Jeremiah Ostriker of Princeton University, Princeton, New Jersey, is that the massive star loses matter via a wind analogous to the stellar wind. No disk would be formed, however. As particles in the wind move outward, those passing in the vicinity of the neutron star could be deflected by the gravitational field and funneled toward the magnetic poles. For either model, the amount of mass transfer necessary to achieve the observed luminosities is relatively small—about 10^{-8} solar masses per year. Although many specific features of Centaurus X-3 and Hercules X-1 still go unexplained, the broad outlines are becoming clearer and it appears that mass transfer in a binary system could energize an x-ray source for a very long time.

Evolution of an X-ray Pulsar

Now that the binary nature of these compact x-ray sources is established, the question might be raised: how do systems come into existence with an old collapsed star accompanied by a young massive star? Two problems are raised by the x-ray pulsars. First, massive stars generally evolve more quickly, but in the Hercules X-1 and Centaurus X-3 systems the less massive component has already reached an endpoint of stellar evolution. Second, neutron stars are presumed to be formed in supernova explosions, but can a star in a binary system collapse to form a neutron star without blowing its companion away?

Close binary stars that transfer matter between them have been known for many years. The fact that the tentative explanation of the evolution of Centaurus X-3 originated more than a decade ago is an indication that it is no longer possible to study x-ray objects without reference to traditional astronomy.

E. Van den Heuvel and J. Heise of the University of Utrecht, Utrecht, Netherlands, have proposed a chronology by which Centaurus X-3, which has an orbital period of 2.17 days, might have evolved. Their explanation is that the neutron star is originally the more massive star, and after several million years of evolution it transfers most of its mass to the companion, and then undergoes a supernova explosion. The binary system remains bound during this explosion because even though the neutron star loses most of its mass, the mass lost is much less than half the entire mass of the system. Finally, several million years after the supernova event, the companion of the neutron star finishes burning hydrogen in its core, and expands. After the companion star fills its Roche lobe, it begins to transfer mass onto the neutron star, and that is when the neutron star becomes an x-ray pulsar.

Specifically, Van den Heuvel and Heise assumed that the system started with a 16-solar-mass star (which later became the neutron star) and a 3-solar-mass star, in a binary system with a 3-day period. After the larger star evolves for 6.85×10^6 years, it will fill its Roche lobe and transfer most of its mass to the companion, until the companion becomes a main sequence star of 15 solar masses and the precursor to the neutron star is left as a helium-burning star of 4 solar masses. The period of the system is changed to 1.5 days. After about 2×10^6 years the helium-burning star evolves and undergoes a supernova explosion. For the purpose of the example, Van den Heuvel and Heise assume that it ejects 3½ solar masses, leaving behind a neutron star with ½ solar mass. The mass of the primary is 15 solar masses, and the period of the system will be adjusted again to conserve angular momentum after the explosion, and will be 2.1 days.

The numbers in the scenario were chosen to be reasonable approximations to the parameters known for Centaurus X-3. The mass of the neutron star in that system is not known, but the period is about 2.1 days and the total mass of both objects at least 15 solar masses.

Out of the grab bag of interesting objects revealed by the x-ray satellites have come two neutron stars accreting matter, one puzzling source of flares, and a curiously syncopated source too slow to be spinning but too fast to be orbiting. They are all in our galaxy. What will further observations bring?

—William D. Metz