Astronomy from an X-ray Satellite: Measuring the Mass of a Neutron Star

Long before radio pulsars were discovered, physicists predicted that a neutron star could not have a much greater mass than the sun. Pulsars are now generally acknowledged to be rapidly rotating neutron stars, but because almost all pulsars appear to be isolated from other stars, no one has been able to measure the mass of a pulsar. However, satellites that scan the sky for pronounced x-ray emissions have revealed several sources of fast and regularly pulsed x-rays in our galaxy. Many scientists think that the x-ray objects are also rotating neutron stars, although in somewhat different conditions than pulsars. But rather than being isolated like pulsars, the x-ray sources are orbiting about other stars in binary systems.

After a year of intensive study of a particular x-ray source, named Hercules *X*-1 because it is found in the constellation Hercules, measurements of the x-ray emissions and the visible light are beginning to meld into a coherent picture. Much more will probably be learned in the future through the powerful combination of x-ray satellites and optical telescopes, but it already seems well established that significant exchanges of energy and gas take place between the neutron star and the visible star in Hercules, and that the neutron star has about the mass of the sun.

Although x-ray astronomy was well established from measurements with rockets in the 1960's, only after x-ray detecting instruments were flown on satellites did the richness of x-ray phenomena become evident. The first U.S. satellite for detecting x-rays was the Small Astronomy Satellite (SAS-A), which was named UHURU after it was launched in December 1970. Experiments with UHURU discovered patterns in the variability of x-ray sources in our galaxy that were almost completely unexpected (*Science*, 28 January 1972), and the satellite is still functioning well. A more recently launched U.S. satellite that also detects x-rays is the seventh Orbiting Solar Observatory (OSO-7). A small instrument for measuring x-rays is one of nine experiments onboard. The impact of the experiments with these two satellites has been immense. In the words of one scientist, "they have had a greater influence on astronomy in the first few years than the 200-inch telescope on Mount Palomar did."

Ironically, just at the time when enthusiasm for x-ray astronomy is growing, plans for future satellites are being curtailed. The third in the series of Small Astronomy Satellites is still scheduled, but a series of larger satellites that would have carried much more sensitive x-ray detectors may not ever be launched. The budget for the High Energy Astronomical Observatory (HEAO) program, which received the highest priority of any space program in a recent evaluation of research in astronomy by the National Academy of Sciences, has been cut by 90 percent.

Regardless of the prospects for the future of x-ray astronomy, new objects are being continually found. Many astronomers think that x-ray sources are most likely to be found in binary systems. At least seven sources found with UHURU show a regular eclipse in the x-ray emission that is characteristic of a binary system. One object known for more than a year, Centaurus *X*-3, exhibits rapid pulsations in addition to regular eclipses. It appears to be the same type of object as Hercules *X*-1, but no companion star has definitely been identified.

Neutron Star in a Binary System

The source Hercules *X*-1 was found by Riccardo Giacconi and his associates, the principal investigators for UHURU, who are at American Science and Engineering Company in Cambridge, Massachusetts. The x-ray emission from Hercules *X*-1 exhibits rapid pulsations every 1.2 seconds that are interrupted every 1.7 days as the companion star passes between the x-ray source and the satellite. The 1.2-second period is presumed to be the period of rotation of the neutron star, and the 1.7-day period is believed to be the period of one complete orbit of the x-ray star and the visible star about each other. However, the x-ray pattern is further complicated by the cessation of the x-ray emissions for about 25 days in every 35 days. The 35-day period is not precise, however. During the 14 months that the source has been observed the period has varied irregularly by 1 or 2 days.

Although Hercules *X*-1 was discovered with UHURU and its three periods were measured with that satellite, data from the satellite OSO-7 was the key to the identification of the companion star. George Clark and his associates at Massachusetts Institute of Technology, Cambridge, who are the principal investigators for the x-ray experiment on OSO-7, were able to establish the position of Hercules *X*-1 within 0.3 degree, an error that is considerably smaller than the error in measurement with UHURU. Whereas the field of view from UHURU is a rectangle ½ degree by 5 degrees, the field of view from OSO-7 is a small circle. However, neither x-ray experiment can specify the location of objects in the sky as accurately as optical telescopes, so even with the improved accuracy from OSO-7 it was necessary to guess which one of many visible stars within the x-ray error circle was the companion of Hercules *X*-1.

William Liller of Harvard University, Cambridge, Massachusetts, suggested that optical astronomers should look at a star known as *HZ* Herculis which had been known for many years. It was classed as a peculiar variable known to be very blue, but no regular fluctuations of its light have ever been observed—simply because there was no compelling reason to look before the x-ray discovery.

In the last year the observations with optical telescopes on the ground have established that fluctuations of the light from the star *HZ* Herculis are indeed very regular—maximum brightness occurs every 1.7 days. At the Tel Aviv University Observatory in the Negev desert, John Bahcall and Neta Bahcall, who are now at the Institute for Advanced Study and Princeton University, Princeton, New Jersey, found that not only does the period of the optical star agree with the period of the x-ray source, but also the optical and x-ray emissions occur in phase with each other. The time of minimum light coincides with the time of minimum x-ray emission within 30 minutes. Liller and his associates have refined the measurement of the optical period to very high accuracy—1.70017 days. The fact that this number agrees with the period of the x-ray eclipse has established unambiguously that the two stars are indeed orbiting about each other.

Now that both halves of the puzzle have been found, a simple model can explain many of the observations of the Hercules system. If the same side of the blue star *HZ* Herculis is always turned toward the x-ray source, as commonly occurs with close binary stars, the facing side could become much hotter than the rest of the star because it would be absorbing a large flux of x-rays (Fig. 1). Because *HZ* Herculis is also orbiting, the hotter and cooler sides would alternately be observed from the earth. In fact, according to the Bahcalls, the variation of the light intensity agrees "embarrassingly well" with the simple curve that describes how much of the surface area on the hot side is projected toward the earth at any time. (Although the inclination of the orbit to the line of sight from the earth is not known, both stars are presumed to pass almost directly through the line of sight since otherwise no eclipse would be observed.)

To determine what might be the mass of the neutron star Hercules *X*-1, John and Neta Bahcall and others have examined the blue star *HZ* Herculis at the time of minimum light. From the spectral type of the side of *HZ* Herculis that does not receive x-rays directly, a number for the mass of the blue star can be determined. This number, plus the detailed small variations of the 1.2-second x-ray pulsations as the source approaches and recedes, is sufficient to estimate the mass of the neutron star. The result is 0.6 solar mass. However, the number could be slightly altered because the spectral type of *HZ* Herculis may not be a precise guide to its mass. Because the blue star is probably transferring gas to the neutron star Hercules *X*-1, and is certainly absorbing x-rays from it, the evolution of *HZ* Herculis—and hence its mass—could be different from the isolated stars that were used to calibrate the standard relationship between mass and spectral type.

A second method of calculating the mass of Hercules *X*-1 depends on small frequency shifts of absorption lines in the blue star that appear because *HZ* Herculis is alternately approaching and receding from the earth in different

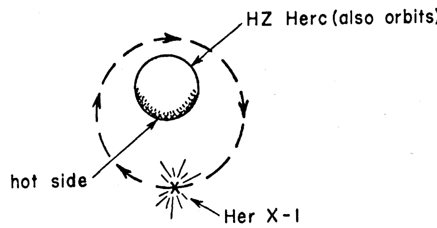

Fig. 1. New measurements have established that the x-ray source Hercules *X*-1 (Her *X*-1), which is thought to be a neutron star, and the blue star *HZ* Herculis (*HZ* Herc) are orbiting each other. The details of the orbit provide an estimate of the mass of the neutron star, and the assumption that one side of *HZ* Herculis is hotter because it intercepts x-rays explains the variations in the blue star's light.

parts of its orbit. This measurement, called the radial velocity, was made by D. Crampton and J. B. Hutchings at the Dominion Astrophysical Observatory in Victoria, British Columbia. The values of the radial velocity of *HZ* Herculis determined in this way are very scattered, however, apparently because gas in the binary system is flowing in random directions. The mass measured from the radial velocity of *HZ* Herculis plus the analogous details of small shifts in the x-ray pulsations is between 0.3 and 0.8 solar mass. According to John Bahcall, one of the goals of optical astronomers for the next year is to make many more measurements of the radial velocity profile of *HZ* Herculis. If the effects of gas movement are random, they should cancel when many measurements are averaged.

The value measured for the mass of Hercules *X*-1 has not surprised anyone, but the newfound facility that astronomers have demonstrated may be very significant. The stability of a neutron star in different theories depends critically on its mass. If the free neutrons in the star do not interact through the nuclear force, the maximum stable mass is 0.7 solar mass. But if nuclear forces are included, the maximum stable mass is 1.5 solar masses. Now that the mass of one neutron star in a binary system has been measured, it would be extremely interesting to see if another star with a mass greater than 0.7 solar mass will be found.

Searches for new neutron stars more massive than Hercules *X*-1 could have far greater significance, however, because of a general theorem explained by Remo Ruffini of Princeton University, Princeton, New Jersey. Ruffini asked what limit could be placed on the maximum mass of a neutron star under the most conservative assumptions—assumptions independent of the details of a particular model of neutron stars. He reported at the recent New York meeting of the American Physical Society that no neutron star can have a mass greater than 3.2 solar masses. The assumptions, according to Ruffini, were that general relativity is the correct theory of gravity and that the velocity of sound in the neutron star is not greater than the speed of light. This means that the discovery of a neutron star more massive than 3.2 suns would have extremely great consequences. As interpreted by Ruffini in New York, either the theory of general relativity or the principle of causality (which states that information cannot be propagated faster than the speed of light) would be called into question. General relativity and the principle of causality make up the core, if not the entirety, of Einstein's work.

To establish the theorem, Ruffini assumed that the neutron star was not rotating. But he argues that the effect of rotation would not change the theorem very significantly. The limit on a neutron star's mass would be increased by 50 percent only in conditions of extremely fast rotation, but the effect of rotation with a period as long as 1 second would be insignificant (1 part in 10^9).

Although Hercules *X*-1 is probably understood better than other x-ray sources, there are still features that are not explained. The origin of the 35-day period in the x-ray emissions is not known. Furthermore, no 35-day optical period has been found. Whatever mechanism turns off the x-ray source for about 3 weeks every 35 days doesn't appear to affect the optical emissions. However, peculiar changes in the optical star apparently have taken place over much longer times. William Liller, Christine Jones, and Bill Forman at Harvard University have looked at old photographic plates taken as long ago as 1890 and found that for periods of months or years *HZ* Herculis stayed at minimum light. So although a very simple model explains many features of the x-ray and optical emissions, some challenges remain.

A few years ago neutron stars were only the dreams of theorists. No one was certain where to look or what to look for. But as a result of astronomy with x-ray detecting satellites, it now appears that scientists can weigh one.

—William D. Metz