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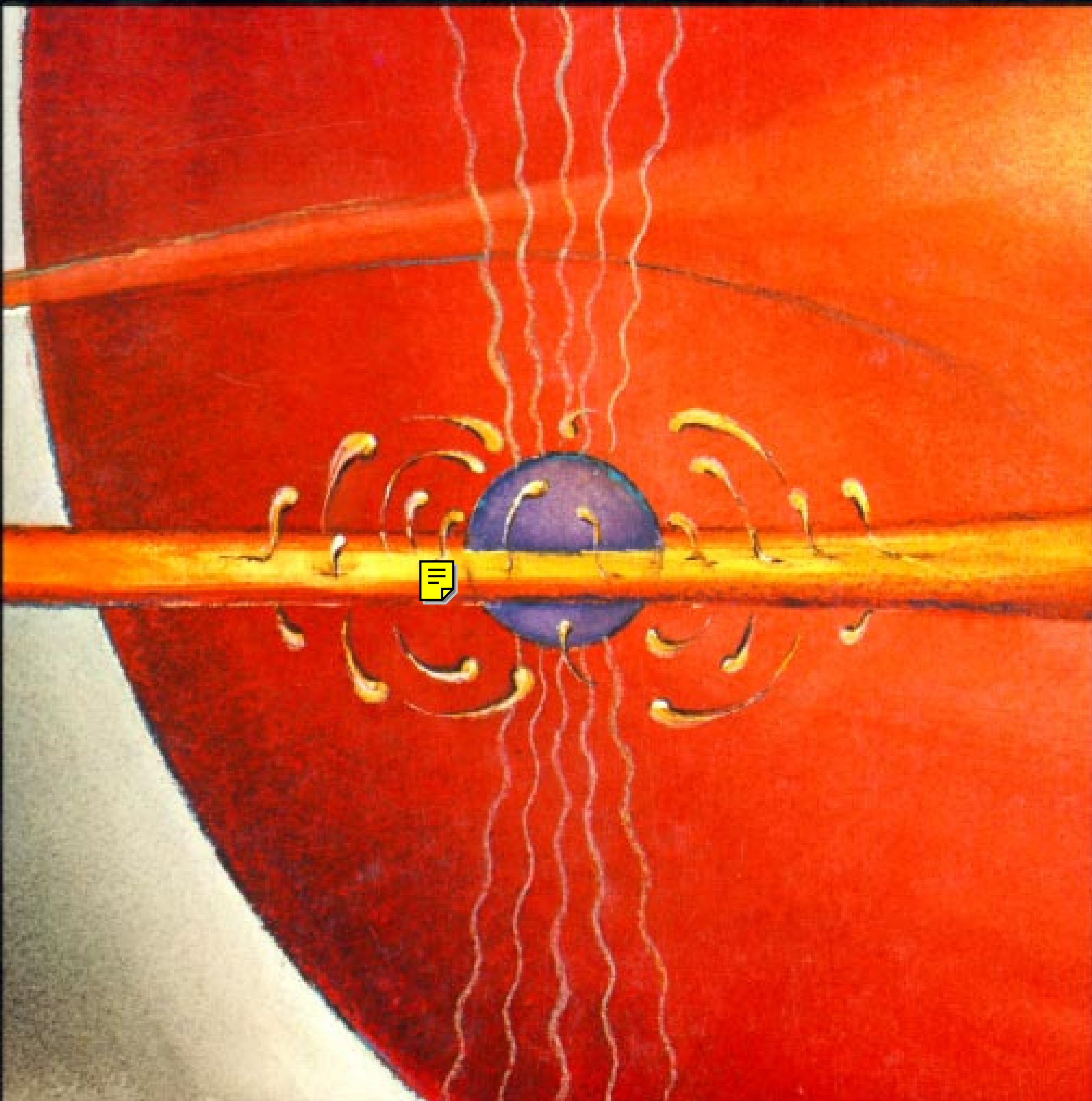
ASTROPHYSICS

Los Alamos Science

LOS ALAMOS NATIONAL LABORATORY



Inside This Issue

Los Alamos has long been a center of astrophysical research. After all, fission and fusion, explosion and implosion, shock waves and hot plasmas are key ingredients in both the physics of the stars and the physics of violent and controlled energy releases on earth.

Many astrophysicists at Los Alamos are occupied with the subject of this issue, the high-energy, high-intensity releases triggered by accretion of matter onto very dense stars. These objects (degenerate dwarfs, neutron stars, and black holes) are made of matter that has been processed by stellar evolution to a final collapsed state of extremely high density and very faint luminosity in the visible part of the spectrum. What makes some collapsed stars the hot spots of the universe is the fall of matter into their deep gravitational potential wells. The gravitational potential energy released by the fall is converted largely into x rays that signal the presence of these almost invisible objects.

As the x-ray universe has come into sharper and sharper focus over the last twenty years, it has become apparent that the process of accretion powers most localized x-ray sources, including pulsing and non-pulsing x-ray stars and the active nuclei of distant galaxies, the brightest of which are quasars. Accretion is the most likely way to explain the enormous energy output of these sources.

The fascination of localized x-ray sources is their dynamic evolution on human time scales. The normal visible stars in the universe change only very slowly, over millions and billions of years. Only by sampling many, each at a different stage of its life, can we infer their path from birth through the steps of thermonuclear burn that make them luminous. X-ray stars are different. Because the matter they contain is in such a concentrated form, physical processes are taking place at higher energies and on shorter time scales. Large variations in x-ray output occur within seconds, hours, days, and months and reveal an astonishing level of detail about the structure and dynamics of the sources.

"X-Ray Variability in Astrophysics," a summary of a Laboratory-sponsored workshop in Taos, New Mexico, last August, reviews the great advances that have been made in this field during the last decade. X-ray stars can now be sorted into well-defined categories: rotation-powered pulsars, accretion-powered pulsars that funnel accreting matter toward their magnetic poles and produce pulsing beams of x rays (see cover), accretion-powered non-pulsing neutron stars whose nature is obscured by coronae, and finally the less energetic but more numerous cataclysmic variables. All but the rotation-powered pulsars are binary star systems in which matter from a normal companion star falls toward a dense star. The information gleaned from bumps and glitches in the x-ray curves include details about neutron-star structure, patterns of accretion flow, sizes, masses, and relative orientations of the binary components, the strengths of magnetic fields, and the dynamics of x-ray bursts. Cyclotron lines in the spectra provide the first direct evidence for very strong magnetic fields (1012 gauss) near the surfaces of neutron stars. Accurate measurements of small changes in the frequencies of pulsars reveal the neutron star as a rigid structure that speeds up and slows down in response to changes in accretion flow. Apparently such flows can reverse direction in times as short as three days! The workshop report is filled with these and other surprising discoveries. As a warm-up to this stimulating but intensive discussion of current developments, the reader may appreciate being reminded of the early history of this field.

X-ray astronomy began with the space age, when rockets carried detectors above the x-ray absorbing layers of our atmosphere. The first experiments were done in the 1940s with captured German V-2 rockets that had been brought to America after World War II and made available for research. By the end of the fifties, x-ray emission from the sun had been recorded throughout an eleven-year sunspot cycle. Since the x-ray luminosity of the sun is a thousand times less than its optical luminosity, detection of x rays from outside the solar system was considered very unlikely by all but a handful of astrophysicists. The possibility of trying became greater as space research was emphasized after the Soviets launched Sputnik in 1957 and the Soviets and Americans resumed atmospheric testing of nuclear weapons in the early sixties. Interest in monitoring the effects of weapon tests spurred the development of x-ray and γ-ray detectors, which then led to the detection of high-energy radiation from cosmic sources.

On June 18, 1962, a rocket was launched from White Sands Missile Range with the express purpose of detecting x rays that might be produced by energetic solar particles impinging on the moon. As the rocket spun on its axis, the line of sight to the detector swept out a great circle. A large signal was recorded coming from the constellation Scorpius, a signal that represented an x-ray luminosity 10,000 times greater than the total luminosity of the sun. This first cosmic x-ray source, named Scorpius X-1, was mysterious indeed. Was it a localized or an extended source, a single star or a group of stars, or a cloud of gas around an invisible star? Was the enormous energy output due to explosion of a star, accretion onto a dense object, or simply thermal radiation from very hot matter?

By 1967 a dozen groups were engaged in x-ray astronomy, and more than thirty sources had been observed. Most seemed to be localized sources, probably collapsed stars. Six were associated with the large clouds of gas and high-energy particles that result from the supernova explosion of a massive star. A few were associated with galaxies millions of light-years away. The accretion of matter from a companion star onto a collapsed star was proposed early on as the energy source of x-ray stars, but this hypothesis was hard to verify. The short duration of rocket observations (five minutes or less for a single object) made it hard to detect the periodic variation of x-ray output that results from the orbital motion of a binary with a likely period of several days. Determining the nature of the collapsed star was also hindered because the theoretically predicted signatures of neutron stars and black holes were not widely appreciated at that time.

The situation was confused by the discovery of radio pulsars in 1967. These objects produce radio pulses with such incredible regularity and with such short periods (tens of milliseconds) that only the rotation or pulsation of a star can explain them. They were soon interpreted as rapidly rotating neutron stars powered by their own rotational energy. Neutron stars were presumed to form when massive stars collapse following supernova explosions. Conservation of angular momentum would lead naturally to their rapid rotation. Moreover, collapse of the star's magnetic field would result in magnetic fields sufficiently strong to produce intense radio waves and x rays. The discovery of a pulsar at the center of the Crab Nebula (a supernova remnant) in both radio and x-ray emissions proved the existence of neutron stars, which had been postulated back in the 1930s to explain supernovae. On the other hand, x-ray stars such as Scorpius X-1 did not seem to pulse, so their nature remained mysterious.

The nature of accretion-powered pulsars was revealed with NASA's launching from Kenya in late 1970 of the first x-ray satellite. It was named Uhuru (the Swahili word for freedom) in honor of Kenya's Independence Day, which coincided with the launch date. The longer observing times and more sensitive detectors provided by Uhuru allowed confirmation of the hypothesis that the energetic x-ray stars are neutrons stars in binary systems. Initial observation of the x-ray star Centaurus X-3 showed x-ray pulsations characteristic of a neutron star, but at a much lower frequency (once every 5 seconds) than the rotation-powered neutron-star pulsar in the Crab Nebula, which rotates once every 0.03 second. Since Centaurus X-3 was putting out the same energy as the Crab pulsar, its source of energy could not be rotational energy alone. However, theoretical calculations showed that such slow spin rates are to be expected for accretion-powered magnetic neutron stars and gave x-ray spectra qualitatively similar to that observed. Further observations revealed a variation in pulse frequency that itself was periodic. This variation was explained as the Doppler shift caused by orbital motion of the pulsar in a binary system, which, in turn, meant that the pulsar could be powered by accretion of matter from the companion star. Eclipses were also observed. Subsequent study of long-term variations in pulse frequency and optical identification of the companion confirmed that Centaurus X-3 is a binary system containing an accretion-powered neutron-star pulsar. Eventually, study of the orbital motions of similar pulsars and their companions allowed researchers to estimate the masses of these neutron stars. They found the masses to be about 1.4 solar masses, in good agreement with the theory of stellar evolution. (Energetic non-pulsing x-ray stars were also shown to have companions, and circumstantial evidence suggests that they are neutron stars, but as yet, there is no way to determine their masses.)

The successes of the early x-ray satellites included the discovery of the first accretion-powered pulsar, of evidence for the existence of black holes at the centers of some x-ray sources, and of x-ray sources well beyond our galaxy, sources at the centers of distant galaxies and sources that extend over entire clusters of galaxies.

We have gone into some detail about the early work on accretion-powered pulsars because it provides a backdrop to

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CONFERENCE REPORT

RESEARCH AND REVIEW

SCIENCE IDEAS

On the cover: Precise measurements of the time variability of x rays arriving at the earth reveal fascinating details about the nature of the sources that generate such radiation (white). The x-ray source here is a neutron star (purple) whose strong magnetic field interacts with material (yellow) that is falling toward it from a large companion star (red).