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Abstract: The article discusses white dwarf stars and supersoft sources of low energy x-rays. Since the 1930s astronomers have known that ordinary stars shine because of nuclear fusion deep in their interior. Recently, however, researchers have discovered a new class of stars in which the nuclear fusion takes place not in the deep interior but in the outer layers just below the surface. These stars appear to be white dwarfs--dense, burned out stars that have exhausted their nuclear fuel-in orbit around ordinary stars. The dwarfs steal hydrogen gas from their companions, accumulate it on their surface and resume fusion. The result is a torrent of x-rays with a distinctive "soft" range of wavelengths; such stars are known as luminous supersoft x-ray sources As the dwarfs gain weight, they eventually grow unstable, at which point they can collapse into an even denser neutron star or explode. The disruption of white dwarfs has long been considered as the cause of one sort of supernova explosion, called type 1a. With the discovery of the supersoft sources, observers have identified for the first time a class of star system that can detonate in its way. Type 1a supernovae have become important as bright "standard candles" for measuring distances to faraway galaxies and thereby the pace of cosmic expansion. Much of the lingering uncertainty in estimates of the age and the expansion rate of the universe is connected to astronomers' ignorance of what gives rise to these supernovae. Supersoft sources may be one of the long-sought missing links. Some theoretical physicists suggested that the supersoft sources were white dwarfs that gave off x-rays as gas crashed onto their surface --much as hard x-ray sources result from the accretion of matter onto a neutron star or into a black hole.

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Supersoft X-ray Stars

Several years ago astronomers came across a new type of star that spews out unusually low energy x-rays. These so-called supersoft sources are now thought to be white dwarf stars that cannibalize their stellar companions and then, in many cases, ex

Since the 1930s astronomers have known that ordinary stars shine because of nuclear fusion deep in their interior. In the core of the sun, for example, 600 million tons of hydrogen fuse into helium every second. This process releases energy in tile form of x-rays and gamma rays, which slowly wend their way outward through the thick layers of gas. By the time the radiation reaches the surface of the star, it has degraded into visible light.

Recently, however, researchers have discovered a new class of stars in which the nuclear fusion takes place not in the deep interior but in the outer layers just below the surface. These stars appear to be white dwarfs-dense, burned out stars that have exhausted their nuclear fuel-in orbit around ordinary stars. The dwarfs steal hydrogen gas from their companions, accumulate it on their surface and resume fusion. The result is a torrent of x-rays with a distinctive "soft" range of wavelengths; suc h stars are known as luminous supersoft x-ray sources As the dwarfs gain weight, they eventually grow unstable, at which point they can collapse into an even denser neutron star or explode.

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The story of the supersoft sources began with the launch of the German x-ray satellite ROSAT in 1990. This orbiting observatory carried out the first complete survey of the sky in soft x-rays, a form of electromagnetic radiation that straddles ultr aviolet light and the better-known "hard" x-rays. Soft x-rays have wavelengths that are one thousandth to one fiftieth those of visible light-which means that the energy of their photons (the unit x-ray astronomers prefer to think in) is between about 0. 09 and 2.5 kiloelectric volts (keV0. Hard x-rays have energies up to a few hundred keV. With the exception of the National Aeronautics and Space Administration's orbiting Einstein Observatory, which covered the energy range from 0.2 to 4.0 keV, previous satellites had concentrated on the hard x-rays.

Almost immediately the ROSAT team, led by Joachim Trüper of the Max Planck Institute for Extraterrestrial Physics near Munich, noticed some peculiar objects during observations of the Large Magellanic Cloud, a small satellite galaxy of the Mil ky Way. The objects emitted x-rays at a prodigious rate-some 5,000 to 20,000 times the total energy output of our sun-but had an unexpectedly soft spectrum. Bright x-ray sources generally have hard spectra, with peak energies in the range of 1 to 20keV, which are produced by gas at temperatures of 10 million to 100 million kelvins. These hard x-ray sources represent neutron stars and black holes in the process of devouring their companion stars. But the soft spectra of the new stars-with photon energies a hundredth of those in other bright x-ray sources-implied temperatures of only a few hundred thousand kelvins. On an x-ray color picture, the objects appear red, whereas classical, hard x-ray sources look blue.

The reason the supersoft sources had not been recognized before as a separate class of star is that the earlier x-ray detectors were less sensitive to low energies. In fact, after the ROSAT findings, researchers went back through their archives and realized that two of the sources had been discovered 10 years earlier by Knox S. Long and his colleagues at the Columbia University Astrophysics Laboratory (CAL), using the Einstein Observatory. These sources, named CAL 83 and CAL 87, had not been classified as distinct from other strong sources in the Large Magellanic Cloud, although the Columbia team did remark that their spectra w ere unusually soft.

Back of the Envelope

AT THE TIME, Anne P. Cowley and her co-workers at Arizona State University surmised that CAL 83 and 87 were accreting black holes, which often have softer spectra than neutron stars do. This suggestion seemed to receive support in the 1980s, when f aint stars were found at the locations of both sources. The stars' brightnesses oscillated, a telltale sign of a binary star system, in which two stars are in mutual orbit. In 1988 an international observing effort led by Alan P. Smale of University Coll ege London found that the brightness of CAL 83 fluctuated with a period of just over one day. A similar project led by Tim Naylor, now at the University of Exeter in England, obtained a period of 11 hours for CAL 87. These visible companion stars are the fuel for the hypothesized black holes. Assuming they have not yet been decimated, the various measurements indicated that they weighed 1.2 to 2.5 times as much as the sun.

But the ROSAT observations suddenly made this explanation very unlikely. The sources were much cooler than any known black hole system. Moreover, their brightness and temperature revealed their size. According to basic physics, each unit area of a star radiates an amount of energy proportional to the fourth power of its temperature. By dividing this energy into the total emission of the star, astronomers can easily calculate its surface area and, assuming it to be spherical, its diameter. It turns out that CAL 83, CAL 87 and the other Magellanic Cloud sources each have a diameter of 10,000 to 20,000 kilometers (16,000 to 32,000 miles)--the size of a white dwarf star. They are therefore 500 to 1,000 times as large as a neutron star or the "horizon " at the edge of a stellar-mass black hole. When Trümper first described the supersoft sources at a conference at the Santa Barbara Institute for Theoretical Physics in January 1991, several audience members quickly made this calculation on the prov erbial back of the envelope.

Some conference participants, among them Jonathan E. Grindlay of Harvard University, suggested that the sources were white dwarfs that gave off x-rays as gas crashed onto their surface--much as hard x-ray sources result from the accretion of matter onto a neutron star or into a black hole. Others, including Trümper, his colleagues Jochen Greiner and Günther Hasinger, and, independently, Nikolaos D. Kylafis and Kiriaki M. Xilouris of the University of Crete, proposed that the sources were neutron stars that had somehow built up a gaseous blanket some 10,000 kilometers thick. In either case, the ultimate source of the energy would be gravitational. Gravity would pull material toward the dwarf or neutron star, and the energy of motion woul d be converted to heat and radiation during collisions onto the stellar surface or within the gas.

Both models seemed worth detailed study, and two of us (van den Heuvel and Rappaport), collaborating with Dipankar Bhattacharya of the Raman Research Institute in Bangalore, India, were lucky enough to be able to start such studies immediately. The conference was part of a half-year workshop at Santa Barbara, where several dozen scientists from different countries had the time to work together on problems related to neutron stars.

It soon became clear that neither model worked. The supersoft sources emit about the same power as the brightest accreting neutron stars in binaries. Yet gas collisions onto neutron stars are 500 to 1,000 times as forceful as the same process on wh ite dwarfs, because the effect of gravity at the surface of a neutron star is that much greater. (For bodies of the same mass, the available gravitational energy is inversely proportional to the radius of the body.) Thus, for a dwarf to match the output of a neutron star, it would need to sweep up material at 500 to 1,000 times the rate. In such a frenetic accretion flow--equivalent to several Earth masses a year--the incoming material would be so dense that it would totally absorb any x-rays.

Neutron stars with gaseous blankets also ran into trouble. Huge envelopes of gas (huge, that is, with respect to the 10-kilometer radius of the neutron star) would be unstable; they would either collapse or be blown away in a matter of seconds or m inutes. Yet CAL 83 and CAL 87 had been shining for at least a decade. Indeed, the ionized interstellar gas nebula surrounding CAL 83 took many tens of thousands of years to create.

Nuclear Power

AFTER WEEKS OF DISCUSSING and evaluating models, none of which worked, astrophysicists realized the crucial difference between accretion of material onto neutron stars or black holes and accretion onto white dwarfs. The former generates much more e nergy than nuclear fusion of the same amount of hydrogen, whereas the latter produces much less energy than fusion. Of the energy inherent in mass (Albert Einstein's famous $E = mc^2$), fusion releases 0.7 percent. Accretion onto a neutron star, howev er, liberates more than 10 percent; into a black hole, up to 46 percent before the material disappears completely. On the other hand, accretion onto a white dwarf, with its comparatively weak gravity, liberates only about 0.01 percent of the inherent ene rgy.

Therefore, on white dwarfs, nuclear fusion is potentially more potent than accretion. If hydrogen accumulated on the surface of a white dwarf and somehow started to "burn" (that is, undergo fusion), only about 0.03 Earth mass would be needed a year to generate the observed soft x-ray luminosity. Because of the lower density of inflowing matter, the x-rays would be able to escape.

Stable nuclear burning of inflowing matter would account for the paradoxical brightness of the supersoft sources. But is it really possible? Here we were lucky. Just when we were discussing this issue, Ken'ichi Nomoto of the University of Tokyo arr ived in Santa Barbara. He had already been trying to answer the very same question in order to understand another phenomenon, nova explosions--outbursts much less energetic than supernovae that cause a star suddenly to brighten 10,000-fold but do not des troy it. Novae always occur in close binaries that consist of a white dwarf and a sunlike star. Until the discovery of supersoft sources, they were the only known close binaries.

For over a decade, Nomoto and others had been improving on the pioneering simulations by Bohdan Paczynski and Anna Zytkow, both then at the Nicolaus Copernicus Astronomical Center in Warsaw. According to these analyses, hydrogen that has settled on to the surface of a dwarf can indeed burn. The style of burning depends on the rate of accretion.

If it is sufficiently low, below 0.003 Earth mass a year, fusion is spasmodic. The newly acquired hydrogen remains passive, often for thousands of years, until its accumulated mass exceeds a critical value, at which point fusion is abruptly ignited at its base. The ensuing thermonuclear explosion is visible as a nova.

If the accretion rate is slightly higher, fusion is cyclic but not explosive. As the rate increases, the interval between burning cycles becomes shorter and shorter, and above a certain threshold value, stable burning sets in. For white dwarfs of o ne solar mass, this threshold is about 0.03 Earth mass a year. In the simulations, fusion generates exactly the soft x-ray luminosity observed in the supersoft sources.

If the rate is still higher, above 0.12 Earth mass a year, the incoming gas does not settle onto the surface but instead forms an extended envelope around the dwarf. Steady burning continues on the surface, but the thick envelope degrades the x-ray s into ultraviolet and visible light. Recent calculations have shown that the radiation is so intense that it exerts an outward pressure on gas in the envelope, causing part of it to stream away from the star in a stellar wind.

If the accretion rate hovers around 0.12 Earth mass a year, the system may alternate between x-ray and visible phases. Exactly this type of behavior has been found in the supersoft source known as RXJ0513.9-6951, which was discovered by Stefan G. S chaeidt of the Max Planck institute. It gives off x-rays for weeks at a time, with breaks of several months. This on/off emission puzzled astronomers until 1996, when Karen A. Southwell and her colleagues at the University of Oxford noticed that the visi ble counterpart to this star fluctuated, too. When the visible star is faint, the x-ray source is bright, and vice versa. The system also features two high-speed jets of matter flowing out in opposite directions at an estimated 4,000 to 6,000 kilometers .per second. Such jets are common where an accretion disk dumps more material on the star than it can absorb. The excess squirts out in a direction perpendicular to the disk, where there is no inflowing matter to block it. The outflow velocity is expected to be approximately the same as the escape velocity from the surface of the star. In RXJ0513.9-6951 the inferred speed nearly equals the escape velocity from a white dwarf--further confirmation that the supersoft sources are white dwarfs.

Soft-Boiled Star

NOT EVERY BINARY SYSTEM can supply material at the rates required to produce a supersoft source. If the companion star is less massive than the white dwarf, as is typically observed in nova-producing systems, the fastest that material can flow in i s 0.0003 Earth mass a year. This limit is a consequence of the law of conservation of orbital angular momentum. As the small companion star loses mass, its orbit widens and the flow rate stabilizes.

For the rates to be higher, the donor star must have a mass greater than that of the dwarf. Then the conservation of angular momentum causes the orbit to shrink as a result of the mass transfer. The stars come so close that they begin a gravitation al tug-of-war for control of the outer layers of the donor. Material within a certain volume called the Roche lobe remains under the sway of the donor's gravity, while material beyond it is stripped off by the dwarf. Perversely, the donor abets its own d estruction. While it sheds mass at the surface, the amount of energy generated by fusion in the core remains largely unaffected. The continued heating from below exerts pressure on the outer layers to maintain the original shape of the star. This pressur e replenishes the material ripped off the dwarf, much as an overflowing pot of soup on a hot burner will continue to pour scalding water onto the stove. The situation stabilizes only when the effects of mass loss are felt by the core itself. For a star o riginally of two solar masses, the return to equilibrium--and thus the cessation of supersoft emission-takes seven million years after the onset of plundering. By this time the star has shrunk to a fifth of its initial mass and become the lesser star in the system. The average accretion rate onto the dwarf in such a case is about 0.04 Earth mass a year.

Following this reasoning, we predicted in 1991 that many supersoft sources would be white dwarfs in tight orbits (with periods of less than a few days) around a companion star whose original mass was 1.2 to 2.5 solar masses. In fact, CAL 83 and 87 are precisely such systems. Since 1992 orbital periods for four more supersoft sources have been measured; all periods were less than a few days. The explanation may also apply to a class of novalike binary systems, called V Sagittae stars, whose oscilla ting brightness has perplexed astronomers for a century. In 1998 Joseph Patterson of Columbia and his collaborators and, independently, Joao E. Steiner and Marcos P. Diaz of the National Astrophysical Laboratory in Itajubá, Brazil, demonstrated th at the prototype of this class of stars has the appropriate mass and orbital period.

There is one other group of star systems that could give rise to supersoft sources: so-called symbiotic binaries, in which the white dwarf is in a wide orbit about a red giant star. Red giants are willing donors. Bloated by age, they have relativel y weak surface gravity and already discharge matter in strong stellar winds. In 1994 one of us (Kahabka), Hasinger and Wolfgang Pietsch of the Max Planck Institute discovered a supersoft symbiotic binary in the Small Magellanic Cloud, another satellite g alaxy of the Milky Way. Since then, a further half dozen such sources have been found.

Some supersoft sources are harder to recognize because their accretion rate varies with time. One source in our galaxy alternates between x-ray and visible emission on a cycle of 40 years, as seen on archival photographic plates. A few objects, suc h as Nova Muscae 1983 and Nova Cygni 1992, combine nova behavior with supersoft emission, which can be explained by a years-long period of sedate "afterburning" between eruptions.

The Seeds of Supernovae

THE COMPANION MASSES required of supersoft sources with short orbital periods imply that they are relatively young systems (compared with the age of our galaxy). Stars of the inferred mass live at most a few billion years and are always located in or near the youthful central plane of the galaxy. Unfortunately, that location puts them in the region thick with interstellar clouds, which block soft x-rays. For this reason, the observed population is only the tip of the iceberg. Extrapolating from th e known number of supersoft sources, we have estimated that the total number in our galaxy at any one time is several thousand. A few new ones are born every 1,000 years, and a few others die.

What happens as they pass away? The fusion of matter received from the companion clearly causes the white dwarf to grow in mass. It could reach the Chandrasekhar limit of about 1.4 solar masses, the maximum mass a white dwarf can have. Beyond this limit, the quantum forces that hold up the dwarf falter. Depending on the initial composition and mass of the dwarf, ther e are two possible outcomes: collapse to a neutron star or destruction in a nuclear fireball. Dwarfs that either lack carbon or are initially larger than 1.1 solar masses collapse. A number of theorists have analyzed this fate.

White dwarfs that do not meet either of these criteria simply blow up. They may slowly amass helium until they reach the Chandrasekhar limit and explode. Alternatively, the helium layer may reach a critical mass prematurely and ignite itself explos ively. In the latter case, shock waves convulse the star and ignite the carbon at its core. And once the carbon burning begins, it becomes a runaway process in the dense, taut material of the dwarf. Within a few seconds the star is converted largely into nickel as well as other elements between silicon and iron. The nickel, dispersed into space, radioactively decays to cobalt and then iron in a few hundred days. Astronomers had already ascribed a kind of explosion to the death of carbon-rich dwarfs--the supernova type Ia. The spectrum of such a supernova lacks any sign of hydrogen or helium, one of the factors that distinguish it from the other types of supernovae (Ib, Ic and II), which all probably result from the implosion and subsequent explosion of massive stars. Type Ia supernovae are thought to be a major source of iron and related elements throughout the universe, including on Earth. Four occur every 1,000 years on average in a galaxy such as the Milky Way.

Before supersoft sources were discovered, astronomers were unsure as to the precise sequence that led to type Ia supernovae. The leading explanations implicated either certain symbiotic stars--in particular, the rare recurrent novae--or mergers of two carbon-rich white dwarfs. But the latter view is now disputed. Although recently double-dwarf systems with the necessary mass and orbital period have been discovered, calculations by Nomoto and his colleague Hadeyuki Saio have shown that such a merge r could in many cases be too gentle to produce a thermonuclear explosion and instead would lead to the formation of a neutron star. Supersoft sources and other surface-burning dwarfs seem a good alternative solution. Their death rate roughly matches the observed supernova frequency. The concordance makes the luminous supersoft binary x-ray sources the first firmly identified class of objects that can realistically be expected to end their lives as type Ia supernovae.

This new realization may improve the accuracy of cosmological measurements that rely on these supernovae to determine distance [see "Surveying Space-time with Supernovae," by Craig J. Hogan, Robert P. Kirshner and Nicholas B. Suntzeff; SCIENTIFIC A MERICAN, January 1999]. Subtle variations in brightness can make all the difference between conflicting conclusions concerning the origin and fate of the universe. The worry for cosmologists has always been that slight systematic errors--the product, per haps, of astronomers' incomplete understanding of the stars that go supernova--could mimic real variations. The implications of the supersoft findings for cosmology, however, have yet to be worked out.

When supersoft sources were first detected, nobody expected that the research they provoked would end up uniting so many phenomena into a single coherent theory. Now it is clear that a once bewildering assortment of variable stars, novae and supern ovae are all variants on the same basic system: an ordinary star in orbit around a reanimated white dwarf. The universe seems that much more comprehensible.

MORE TO EXPLORE

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GRAPH: SOFT AND HARD x-ray sources are distinguished by their spectra, as measured by the ROSAT orbiting observatory. A typical supersoft source emits x-rays with a fairly low energy, indicative of a comparatively cool temperature of 300,000 degree s Celsius.

GRAPH: A typical hard x-ray source is 100 times hotter and therefore emits higher-energy x-rags. In both cases, the intrinsic spectrum of the source is distorted by the response of the ROSAT detector and by interstellar gas absorption.

GRAPH: ON/OFF EMISSION of supersoft star RXJOS13.9-6951 is a sign that it is poised between two different modes of behavior.

GRAPH: When it shines brightly in visible light, its x-rag output is low, and vice versa. [The lower x-ray counts are upper limits.) The star is at the border between a pure supersoft source [which would emit only x-rays) and a white dwarf surrounded by thick gas [which would emit only visible light]. Slight fluctuations in the rate of gas intake switch the star from one behavior to the other.

GRAPH: STYLE 0F NUELEAR FUSION on the surface of a white dwarf depends on how massive the dwarf is and how fast it is devouring its companion star [vertical axis]. If the accretion rate is sufficiently low, fusion [which astronomers misleadingly ca ll "burning"] occurs in spurts, either gently or explosively.. Otherwise it is continuous. As shown above, phenomena once thought to be distinct--such as novae and supersoft sources--are closely related.

DIAGRAM: COMPACT STARS have colossal escape velocities. A typical white dwarf packs the mass of the sun into the volume of a planet. To break free of its gravity, an object must travel at some 6,000 kilometers per second. This is also about the speed that a body doing the reverse trip--falling onto the dwarf from afar--would have on impact.

DIAGRAM: Denser stars, such as neutron stars with the same mass, have an even mightier grip.

DIAGRAM: The densest possible star, a black hole, is defined by a "horizon" from which the escape velocity equals the speed of light.

DIAGRAM: LIFE CYCLE of a supersoft star begins with an unequal binary star system and ends with a type la supernova explosion. The supersoft phase can take one of three forms, depending on the companion star. If it is an ordinary star in a tight or bit, it can overflow its Roche lobe and cede control of its outer lagers to the white dwarf.

DIAGRAM: If the companion is a red giant star of sufficient size, it also overflows its Roche lobe.

DIAGRAM: Finally, if it is a red giant with a smaller size or a wider orbit, it can power a supersoft source with its strong winds. Hot all supersoft sources blow up, but enough do to account for the observed rate of supernovae.

PHOTO (COLOR): DAVID AND GOLIATH STARS form a symbiotic binary system: a white dwarf and a red giant star in mutual orbit. The dwarf, with its intense gravity, is slurping off the outer layers of the giant. The pilfered gas goes into an accretion disk around the dwarf and eventually settles onto its surface, whereupon it can ignite nuclear fusion and generate a large quantity of low-energy x-rays.

PHOTO (COLOR): X-RAY COLOR IMAGE shows how a nearby mini galaxy, the Large Magellanic Cloud, might appear to someone with x-ray vision. A red color denotes lower-energy [or, equivalently, longer-wavelength] radiation; blue means higher energy {shor ter wavelength]. Supersoft sources stand out as red or orange dots; hard x-ray sources look blue. The supersoft star CAL 87 seems green because a cloud of hydrogen alters its true color. [Some red dots are actually sunlike stars in the foreground.

PHOTO (COLOR): The view is rather different from an ordinary photograph of the area.

PHOTO (COLOR): Pair of ordinary stars burn hydrogen in their cores

PHOTO (COLOR): One exhausts fuel in core, becomes red giant

PHOTO (COLOR): Orbit tightens; giant envelops other star

PHOTO (COLOR): Giant sheds outer layers, becomes white dwarf

PHOTO (COLOR): Dwarf steals gas from other star, emits soft x-rays

PHOTO (COLOR): Dwarf reaches critical mass, explodes

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By Peter Kahabka; Edward P. J. van den Heuvel and Saul A. Rappaport

PETER KAHABKA, EDWARD P. J. VAN DEN HEUVEL and SAUL A. RAPPAPORT never thought supersoft sources would be explained by white dwarfs. That insight came about during a workshop that van den Heuvel and Rappaport organized on a different topic: neutron stars. Two years later these veteran astronomers met Kahabka, who had discovered many supersoft sources as a member of the ROSAT team. Today Kahabka is research associate at the University of Bonn in Germany. Van den Heuvel is director of the Astronomic al Institute at the University of Amsterdam and the 1995 recipient of the Spinoza Award, the highest science award in the Netherlands. An amateur archaeologist, he owns an extensive collection of early Stone Age tools. Rappaport is a physics professor at the Massachusetts Institute of Technology. He was one of the pioneers of x-ray astronomy in the 1970s.
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