search & discovery

Evidence accumulates for a black hole in Cygnus X-1

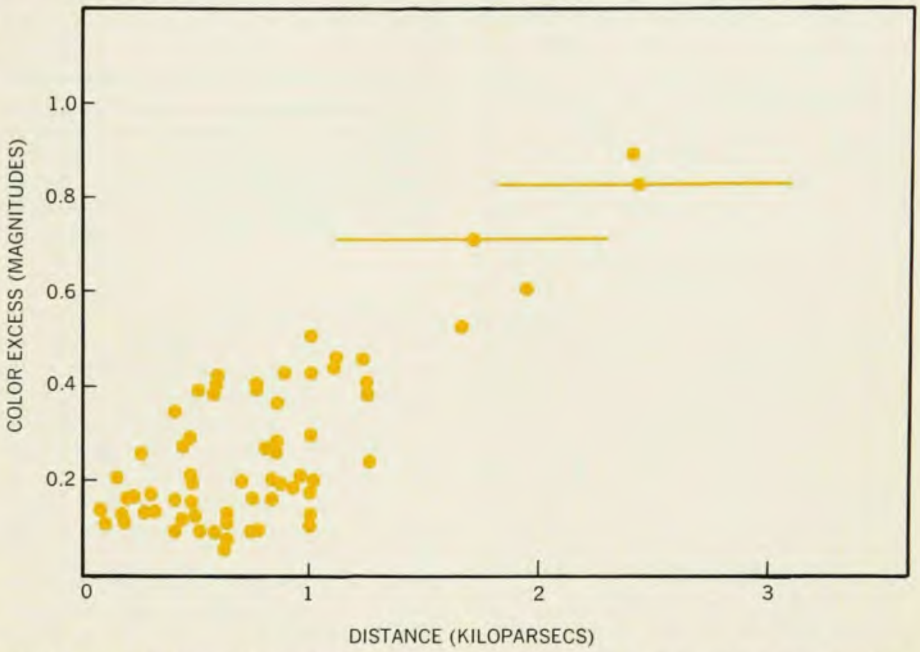
Within the past year many observers have become convinced that Cygnus X-1 contains a black hole. The most recent evidence, reported at the December meeting of the American Astronomical Society in Tucson, is from an x-ray detector aboard a rocket; a group at the Goddard Space Flight Center reported seeing millisecond variations in intensity, suggesting a compact object. Other recent evidence has come from observations with the 61-cm telescope at the Lick Observatory and from a group at University College London, who have an x-ray telescope aboard the Copernicus satellite. As the evidence has mounted, so has the excitement. However, there are many holdouts taking a wait-and-see attitude.

The x-ray source Cygnus X-1 had been detected in early surveys in 1963–67. Then at the beginning of 1971, using the Uhuru satellite, a group at American Science and Engineering discovered the existence of large-amplitude x-ray pulsations; they concluded that the source was a collapsed object. This finding prompted many subsequent observations in x-ray, optical and radio wavelengths.

The next major step came when Cygnus X-1 was identified with the ninth-magnitude, 5.6-day period spectroscopic binary HDE 226868. An accurate measurement of position had been obtained by Uhuru. This position was refined with greater accuracy in a rocket flight by Saul Rappaport (MIT) and his collaborators, who obtained an error box of about 30 arcsec. Right in the middle of the error box is a radio source, which was observed to turn on in the spring of 1971, going from below detectable limits to a reasonably strong radio source at the same time (within a week of each other) as the x-ray intensity reported by Uhuru decreased by a factor of four. Since then the average level of both the x-ray and radio signals has been relatively unchanged. The radio source had been discovered by Robert Hjellming and Campbell Wade of the National Radio Astronomy Observatory and by L. Braes and G. K. Miley of Westerbork Observatory in the Netherlands.

In addition to the radio source being identified with the x-ray source, Thomas Bolton (David Dunlap Obser-

continued on page 19



Color excess (reddening) as a function of distance for stars in the vicinity of HDE 226868. Horizontal lines correspond to uncertainties in the distance measurement. The color excess for HDE 226868 is 1.12, suggesting that its distance is at least 2.5 kiloparsec, that HDE 226868 is at least 30 $M_{\odot}$ and that the mass of its companion star is at least 6 $M_{\odot}$. Figure is adapted from J. Bregman, D. Butler, E. Kemper, A. Koski, R. P. Kraft, R. P. S. Stone, Ap. J. **185**, L 117 (1973), copyright 1973 by the American Astronomical Society.

Nuclear-magnetism studies at Saclay

A unique research effort at Saclay, headed by Anatole Abragam, is using the method of dynamic nuclear polarization to study nuclear ferromagnetism and antiferromagnetism and to observe so-called pseudomagnetism. The experiments on nuclear ferromagnetism and antiferromagnetism have yielded spin temperatures of a microdegree Kelvin or lower, achieving a record low temperature duly recorded in the "Guinness Book of World Records."

Furthermore, according to Harvard's Robert Pound, the Saclay group is the first to observe an ordered magnetic state due only to nuclear dipole–dipole interactions. The pseudomagnetism research now allows the systematic measurement of spin-dependent amplitudes for the scattering of neutrons by nuclei.

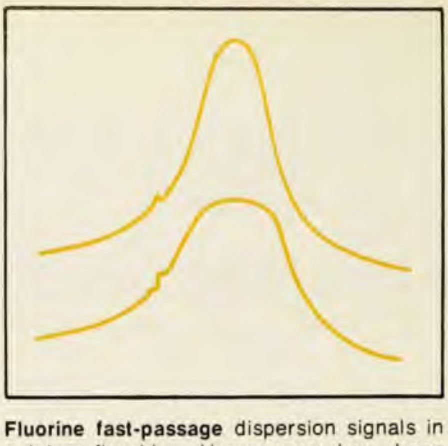
When we recently visited Abragam at the Centre d'Études Nucleaires de Saclay outside of Paris, he told us that he has been working in nuclear magnetism, the study of nuclear magnetic moments in bulk matter, since shortly after Felix Bloch and Edward Purcell did their pioneering work in nuclear magnetic resonance. Abragam, who is also professor of nuclear magnetism at the Collège de France, said that the research effort at Saclay on nuclear magnetism is not being done anywhere else in the world. "There is the danger that no one else is doing it because it's not interesting. On the other hand, some of the things we're doing I don't think anyone else could do." What is needed, he said, is access to a nuclear reactor, well-developed cryogenic, microwave and nmr techniques, and moderately sophisticated equipment.

The Saclay group uses the method of dynamic nuclear polarization, invented 15 years ago independently by Carson D. Jeffries (University of California, Berkeley) and by Abragam. With this technique it is possible to increase the polarization of nuclear spins to 90% or higher. (The approach has been widely used to produce polarized targets for nuclear and high-energy physics.) Under ordinary conditions, because the nuclear magnetic moments are 10^{-3}–10^{-4} the size of atomic magnetic moments, nuclear magnetism is a very weak phenomenon, and the degree of orientation is only say 0.25% in a field of 25 kOe and a temperature of 1 K.

Nuclear magnetic ordering. Four years ago M. Chapellier, M. Goldman, Vu Hoang Chau and Abragam reported[1] the observation of a nuclear antiferromagnetic state in calcium fluoride. Now in recent work still in progress J. F. Jacquinot, W. T. Wenckebach, Chappelier, Goldman and Abragam say they have observed[2] nuclear ferromagnetism in calcium fluoride. There is great interest in the study of ordered states resulting from dipolar interactions only, the experimenters point out. The form and strength of such interactions is known exactly and gives a "clean" problem where, at least in principle, the comparison between the calculated and observed values of various parameters can be made unambiguously. One is working with new, unstudied phase transitions, a prospect that should prove interesting to many-body theorists.

In ordinary ferromagnetism, for an ordered state to appear, the energy of a given magnetic moment in the local field of its neighbors must be larger or equal to kT_c, where T_c is the critical temperature. Above T_c there is no long-range order. When ordering occurs, the spins can all point in the same direction and one gets ferromagnetism. And if the system breaks into sublattices, half pointing up and the other pointing down, the ordering is antiferromagnetic. To achieve the result with nuclear magnetic moments, it can be shown theoretically that the temperature must be approximately 1 microdegree. Abragram stresses that it is the nuclear spins that are cooled by such an amount, not the molecular motion of the crystal lattice. Furthermore it would be meaningless to talk about such a low temperature for the lattice, he notes, because when one reaches 1 millidegree all the gross properties of the crystal are frozen in.

The technique the Saclay team uses is a two-step process. First they produce an initial lattice temperature of 1 K in high magnetic field and then they dynamically polarize the F^{19} spins to a polarization of about 90%. This can be interpreted as giving the fluorine spins a temperature of about 1 millideg. In the second stage they use adiabatic nuclear demagnetization in a rotating frame to reduce the spin temperature to 1 microdeg or less. With this approach they apply a radiofrequency field and sweep the magnet through resonance. In an ordinary case there is a bell-shaped resonance response, which is the amplitude of the nuclear magnetization in phase with the rf field. But when ferromagnetic or antiferromagnetic ordering occurs, the experimenters get a flat top.



Fluorine fast-passage dispersion signals in calcium fluoride. Upper curve has shape characteristic of resonance in which a cooperative transition does not occur. Lower curve has a flattop that is evidence for an antiferromagnetic transition (reference 1).

Abragam explained how they know they are seeing ferromagnetism in the new experiment. They observe domains of a few 1000 Å in size, he said; that is, the breaking up into plus and minus regions takes place on a much larger scale than the few ångstroms associated with antiferromagnetism. To tell that this is what they are seeing, they do nmr measurements on the rare isotope of calcium, Ca^{43}, which is present in the CaF_2 in the amount of about 0.1%. The abundant Ca^{40} has no nuclear spin, but the Ca^{43} has spin 7/2. The Ca^{43} sees not only the applied field but also the local field produced by the fluorine. This local field has opposite sign in adjacent domain sections. Hence the Ca^{43} nuclei in a positive domain see a somewhat different field from those that are in the opposite direction. Experimentally not one resonance line is observed but two. And as the spin temperature rises, the two lines come together.

Nuclear pseudomagnetism. The existence of atomic antiferromagnetism was first demonstrated by neutron scattering experiments, much of them done by Clifford Shull (MIT) in the early 1950's. Because the neutron has a magnetic moment, it will scatter differently from an atomic plane with spins up than one with spins down. So one will see extra lines in the neutron diffraction Bragg spectrum. The Saclay group decided to do the same thing with nuclear magnetic moments. If purely magnetic, the effect would be much smaller. In fact the nuclear magnetic cross section would be expected to be 10^{-6}–10^{-8} as small as the cross section for atomic magnetic scattering.

Abragam told us that he introduced the concept of a pseudomagnetic moment of the nucleus, which is that hypothetical magnetic moment that would scatter a neutron magnetically with an amplitude equal to the actual nuclear scattering. (He finds that the pseudomagnetic moment of the proton, for example, is 3600 times stronger than its real magnetic moment.) From this magnetic analogy, he argues that one would expect that a neutron going through a polarized nuclear target will see a pseudomagnetic field. Thus the neutron passing through the sample will have a precession caused by the sum of the applied field and the nuclear field; it is this quantity that Abragam and his collaborators have measured.

Their first experiments, done by Abragam, G. L. Bacchella, H. Glattli, P. Meriel, J. Piesvaux and M. Pinot, were reported[3] in 1972. In this work they demonstrated the reality of the pseudomagnetic field by a resonance experiment in a sample of lanthanum magnesium double nitrate, in which the protons of the water of crystallization were polarized dynamically to about 50%. Because a large pseudomagnetic field was produced, the neutron precession frequency in the system was raised much higher than that corresponding to the external field. To show that the neutrons were indeed precessing with this frequency, they applied a radiofrequency pseudomagnetic field to turn the neutrons over. This was accomplished by forcing the protons, which produced the pseudomagnetic field, to precess themselves around the direction of the external field (by applying a small rf field to the proton). Then the pseudomagnetic vector has a transverse component that will precess coherently with the proton polarization. The sweep through resonance was achieved simply by allowing the dynamic polarization to decay, correspondingly reducing the pseudomagnetic field. The proton frequency, which is not sensitive to the pseudomagnetic field, remains fixed. When the resonance is reached, they observe a dip in the spin polarization of the transmitted neutrons.

Recently the same Saclay group has reported[4] a new way of measuring the pseudomagnetic moment and checked it out with hydrogen and vanadium. Using the concept that a neutron will precess in the pseudomagnetic field, they first flip with an rf coil the neutron spins perpendicular to the external field, so as to make them precess; then they look for an additional precession angle, due to the pseudomagnetic field, which will show up as a change in the efficiency of flipping back the neutron spins in a second transition region. They are able to observe pseudomagnetic fields much smaller than in the preceding experiment, such as those associated with thermal equilibrium polarization in a magnetic field rather than with a dynamically polarized system.

Earlier experiments by others had measured the spin-dependent neutron scattering amplitude for hydrogen, deuterium, vanadium and cobalt. The Saclay workers have applied the pseudomagnetic precession technique to F^{19}, aluminum, Li^7 and sodium, and they plan to extend their technique to other materials.

Pound feels that the Saclay group now has a systematic tool for measuring spin-dependent neutron scattering amplitudes for all sorts of nuclei. —GBL

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Black hole

continued from page 17

vatory, Toronto) and independently, Louise Webster and P. Murdin (Royal Greenwich Observatory) studied the star HDE 226868, which was located at the radio position. They observed the optical spectrum of this ninth-magnitude star and found that the Doppler shift varied with a period of 5.6 days, suggesting that the star had some companion orbiting around it. Bolton found emission lines that were Doppler shifted in a way that indicated gas was flowing from the visible star to the companion.

New evidence for the identification of the optical and x-ray sources was recently announced by NASA, which reported that a University College London group, headed by Robert L. F. Boyd and Peter Sanford, using the Copernicus satellite, had correlated the variation in x radiation from Cygnus X-1 with the optical radiation and found evidence of the visible star's gas clouds swirling around and into a black hole. During three different 5.6-day periods the University College group observed the x-ray output from Cygnus X-1 in soft x rays at 6–20 Å (0.5–1.0 keV) and hard x rays, 1–3 Å (3–10 keV). In the soft x rays they observed a dip in intensity with a 5.6-day period. With the hard x rays they observed a similar but smaller dip in intensity near zero phase, where the x-ray source is on the other side of the optical companion. Earlier observations by Uhuru in hard x rays (2–20 keV) found no periodic intensity variations. Because higher energy x rays can penetrate more easily, there is less reason to expect to have much of an occultation effect in harder x rays.

Mass of x-ray source. If it is assumed that the ninth-magnitude star is a binary companion of the x-ray source, then using ordinary Newtonian dynamics of the binary system, one can infer something about the mass of the x-ray source, which is not observed optically. Assuming that the ninth-magnitude star is a B0 supergiant with a mass of about 30 $M_\odot$, one can determine the mass of the x-ray object to be greater than about 6 $M_\odot$.

(It is generally believed that a compact object must have a mass of at least 3 $M_\odot$ for us to be sure it is a black hole. There is a fairly well established upper limit for the mass of a nonrotating white dwarf—1.2 $M_\odot$ and for the mass of a neutron star—1.7 $M_\odot$; these limits can be increased somewhat if the objects are allowed to rotate very rapidly, but there are various arguments against being able to get as high as 6 $M_\odot$ in this way.)

The uncertainty in all these calculations, though, was whether the mass of the ninth-magnitude star was indeed 30 $M_\odot$, because there were other possibilities. For example, you could instead have a more highly evolved star of much smaller mass, which could mimic the optical appearance of a B0 supergiant with 30 $M_\odot$, provided it were much nearer. If that were the case, the mass of the x-ray source would also be much less.

Now with two companion reports from the Lick Observatory, published in the 1 November issue of *The Astrophysical Journal Letters* (by Bruce Margon, Stuart Bowyer and Remington P. S. Stone and by Jesse Bregman, Dennis Butler, Edward Kemper, Alan Koski, Robert P. Kraft and Stone), a better distance estimate of the binary system has established that the ninth-magnitude star is 30 $M_\odot$. These papers confirmed earlier distance estimates obtained by Bolton and by H. Smith, Margon and Peter Conti (Lick Observatory). In the new Lick work the observers looked at a large number of ordinary main-sequence stars in the same general direction in the sky and plotted the amount of reddening for these stars against distance, getting approximately a straight line. The reddening increases with distance because of interstellar dust along the line of sight. With Cygnus X-1 the amount of reddening is greater than any of the other stars; this implies that Cygnus X-1 is probably at least 2.5 kiloparsec away. This means that the ninth-magnitude star is at least 30 $M_\odot$, is indeed a B0 supergiant and that the mass of the x-ray source is at least 6 $M_\odot$.

Kraft pointed out to us some recent work by Jeremiah Ostriker (Princeton University) and Edward van den Heuvel (Astronomical Institute at Utrecht) that argues that if the B0 supergiant were burning helium in the core rather than hydrogen in a shell source, the mass could be as small as 10 $M_\odot$, in which case the mass of the unseen x-ray source would be 3.8 $M_\odot$.

The most recent evidence that Cygnus X-1 contains a black hole, reported at the Tucson meeting by Stephen Holt, Richard Rothschild, Elihu Boldt and Peter Serlemitsos of Goddard Space Flight Center, is that its x-ray output is flickering with variations as short as a millisecond, a behavior characteristic of a very small object. Previously the shortest variations observed in Cygnus X-1 were about 50 millisec; these were reported by the MIT group. A more recent analysis of the MIT data by Minoru Oda (University of Tokyo) and his collaborators, presented at the October meeting of the Astronomical Society of Japan, "indicate the existence of a number of flares with a duration of less than one millisecond." The Goddard team looked at Cygnus X-1 for about 1 minute with a large x-ray detector mounted on a rocket. They reported finding eight statistically significant bursts with duration about 1 millisec; during this time the intensity increases were as large as an order of magnitude. The bursts are superposed on slower variations, which had previously been reported by others.

Theory. Martin Rees (Plumian Professor of Astronomy at Cambridge University) told us that the x-ray behavior of Cygnus X-1 is just what you would expect from the most popular model. This says that gas is being captured from the companion star and forms a disc swirling around the black hole. Because of the viscosity of the disc, each element of the gas gradually loses angular momentum and spirals inward. Before the gas is gobbled up by the black hole, it gets very hot and emits x rays. Furthermore, the flickering on a rapid time scale can be explained, Rees said, because the orbital period of the gas just before it disappears is expected to be about a millisecond. On the other hand, a true periodicity, such as is seen from a neutron star, is not expected from a black hole because it has no hard surface, Rees notes; so he feels that it is gratifying that no periodicity has been observed in the flickering.

Despite the widespread conviction that a black hole has at last been found, some serious objections have