search & discovery

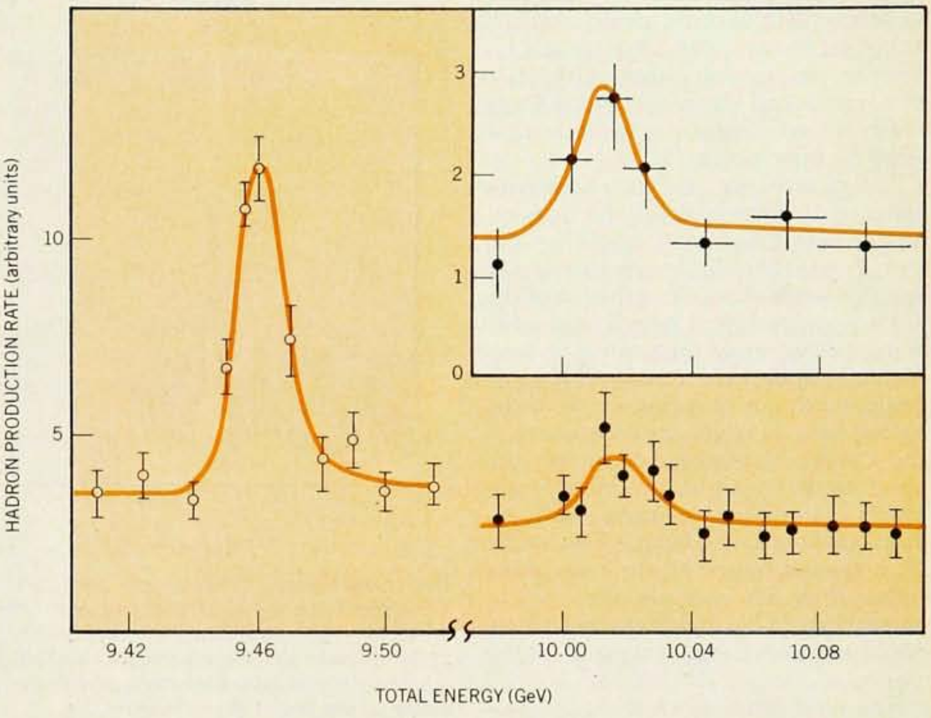
DESY verifies two upsilon states; evidence for fifth quark

By stretching the energy limits of the DORIS storage ring to its fullest, experimenters at DESY in Hamburg have observed the upsilon and upsilon prime at roughly the masses reported in 1977 by Leon Lederman and his collaborators (PHYSICS TODAY, October 1977, page 17)—9.46 and 10.02 GeV/c^2. But the new experiments have 20 times better energy resolution, primarily because they are done in an e^+e^- storage ring.

The new observations are generally taken as further evidence for the existence of a fifth quark, known as "bottom" whose charge is $-\frac{1}{3}e$. Knowing the exact mass difference between the Υ and Υ' gives further clues as to the nature of the force between quarks. The popular theory, quantum chromodynamics, assumes that the underlying force is the same for all quarks, regardless of their flavor (up, down, strange, charm, bottom, the predicted top, . . .).

The DORIS experiments provide an added fillip: Observations with PLUTO, DASP-2 and the NaI Lead-Glass Detector all show that outside the narrow energy region of the upsilon resonances, jets are

continued on page 19



Hadron production rate at DORIS versus total energy as observed by the NaI Lead-Glass Detector (bottom curves) and DASP-2 Detector (inset). The Υ yield measured by the NaI Lead-Glass Detector is included with the same scale and acceptance. Note the Υ' at 10.02 GeV from both experiments.

Satellite and Chilean telescopes correlate x-ray burst

Beginning in late 1975, astronomers have detected intense, brief, and often repetitive bursts of x rays from an ever-increasing number of pointlike sources. Recently a Harvard–MIT group reported observing an optical burst correlated with such an x-ray burst. Meanwhile, analysis of ten of the 30-odd known x-ray bursters has revealed a surprising degree of uniformity among them. Work on theoretical models is also proceeding, and at least one model has recently given good agreement with the observed properties of the bursters.

X-ray bursters were first observed with the Astronomical Netherlands satellite, which has since been turned off, and confirmation quickly came from the SAS-3 orbiting observatory, which still provides much of the data on the bursters. Other discoveries followed soon after (PHYSICS TODAY, April 1976, page 17), with most of the sources lying roughly in the direction of the galactic center. A few of the sources appear to be associated with globular clusters, and five have been identified with faint blue star-like objects. Typically, the bursts rise in about a second to a peak intensity about 10 to 50 times the steady emission and die down over several seconds or even minutes. All the bursters repeat, some of them with fairly regular periods of hours or days; others burst erratically, and many of the sources turn off for periods of days, months or perhaps years.[1]

The first optical burst. A group composed of Jonathan Grindlay (at the Harvard–Smithsonian Center for Astrophysics) and Jeffrey McClintock, Claude Canizares, Jan van Paradijs, L. Cominski, Fuk Kwok Li, and Walter H. G. Lewin (all at the Center for Space Research at MIT) observed[2] a simultaneous optical and x-ray burst from one of the known sources; the event was also reported at a meeting of the High Energy Astronomy Division of the American Astronomical Society in La Jolla in September. The x-ray burster MXB 1735 − 44 is associated with a steady source, 4U 1735 − 44, as well as a faint blue star-like object. The identification of the burster with the "star" was made possible by a very precise determination of the burster's position by another group at MIT.[3] In early June, Grindlay, McClintock, and Canizares used the 1.5-m telescope at Cerro Tololo Inter-American Observatory to monitor the stellar object; simultaneously, van Paradijs, Cominsky, Li and Lewin were working in Cambridge on the x-ray data transmitted from SAS-3. The group in Chile saw two optical bursts, but the first occurred while SAS-3 was dumping data to a ground station, so that only the second optical burst can be correlated with an x-ray burst.

The group in Cambridge saw a second x-ray burst during the observation period, but because twilight had already set in at Cerro Tololo, the group in Chile could detect no optical burst above the background illumination. Except for the observed bursts, the optical activity showed no change during the three nights of observation, even though the burster had started x-ray activity by the second.

Lewin's group organized an optical–x-ray search a year ago during which it discovered the blue star-like objects associated with three of the bursters but saw no optical bursts. The detection and recording equipment that Grindlay, McClintock and Canizares used in Chile this year was an order of magnitude more sensitive than last year's.

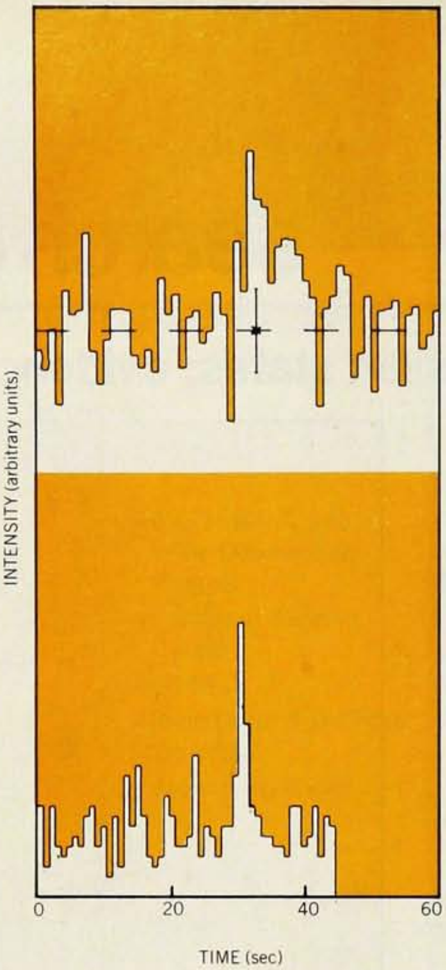
The most recent analysis of the data indicates that the optical burst rises approximately 2.8 seconds later than the x-ray burst (although the exact amount of delay depends on just how the rise of the burst is defined) and decays somewhat more slowly. From the relative intensities of the optical and x-ray emissions the group concludes that the source of the optical burst is larger than the source of the x rays. Canizares told us that the observed delay and the presumed larger source of the optical emission clearly indicate that the optical burst is a secondary phenomenon caused by the x-ray burst rather than, for example, the low-frequency tail of a blackbody emission whose high-frequency component is seen in the x rays.

The most likely mechanism for producing the optical burst, Canizares said, is some form of fluorescence. The x-ray source is, presumably, a compact object such as a black hole or neutron star. It is surrounded by a disk or shell of accreting material and possibly accompanied by a dim stellar companion. The companion or the cloud of accreting material would be the faint blue object observed in the visible. The copious x rays from a burst may heat the cloud or the companion, and the increased incandescence represents the visible pulse.

Size of the bursters. The x-ray bursts decay at different rates in different frequency ranges. In general, the spectrum softens in time, an effect that can be understood as due to a cooling of the source. Last year Jean Swank and co-workers at the Goddard Space Flight Center and Jeffrey Hoffman (now in training as a scientist–astronaut for the Space Shuttle) and a group at MIT showed that for at least a few sources the luminosity and temperature decrease together, with L roughly proportional to T^4, which is what one would expect from a cooling blackbody.

Van Paradijs (of the University of Amsterdam, but currently at MIT) has studied ten of the bursters in considerable detail[4] and confirmed that $L \propto T^4$ for all of them. In particular, van Paradijs found that $T^{-4}F/F_{max}$ (where F is the total x-ray flux at any time and F_{max} is the peak flux during the burst) remains constant during any burst and is the same for all ten sources. Furthermore, the peak luminosity of any burster varies by no more than a few tens of percent from burst to burst. Van Paradijs thus concludes that the peak luminosities may well be limited by some general phenomenon and that the peak luminosity may therefore be the same for all burst sources.

If the radiation is thermal, Stefan's law can be used to determine the size of the source once its absolute luminosity is known. The models for the origin of the bursts suggest that the peak luminosity is, to within an order of magnitude, given by the Eddington limit, at which the gravitational and radiation pressures are equal near the surface. The Eddington limit depends on the mass of the object, and for the bursters whose distances can be estimated, the masses turn out to be around $1\frac{1}{2}$ to $2\frac{1}{2}$ solar masses. Van Paradijs suggests that the remaining bursters in his sample are sufficiently similar to those whose distances can be estimated that they may also be assumed to have a mass around $1\frac{1}{2}\ M_{\odot}$. The result of this assumption is that all bursters then also have the same radius, about 10 km. If the radiation is not strictly thermal but only "gray" body radiation, van Paradijs's argument gives a lower limit on the size of the sources; the source itself may, of course also be only a part of a larger object.



Correlated bursts. Optical (upper graph) and x-ray intensities as functions of time after UT 06:48:41. The optical data are from a detector at Cerro Tololo with spectral range 3100–5500 Å. The x-ray data are from the 5–10 keV detector aboard SAS-3 (figure from ref. 2).

Models. The model that has received the most attention lately is one in which the burst is due to a brief flash of thermonuclear fusion in the dense matter accreting on the surface of a neutron star. The idea is that as the material accumulates it is compressed and heated and will undergo thermonuclear fusion. Under a wide range of circumstances the process is unstable and produces explosive flashes. We see the thermal x rays emitted when the energy of the flash works its way to the surface of the star. Paul C. Joss of MIT told us that it is generally assumed that the accreting material is supplied by a companion star, too small to be an ordinary luminous star. Its primary function would be to supply the compact object with further matter and perhaps to glow in the light of the x-ray emission from the compact object. Joss has been working on this model,[5] and his most recent detailed calculations give remarkably good agreement with the gross properties of the x-ray burst.

Joss's calculations assume that material, mostly helium, falls onto a neutron star of about $1\frac{1}{2}$ solar masses and $6\frac{1}{2}$-km radius. The star is not rotating and has a neglible magnetic field, so that the accretion is spherically symmetric. Using a standard code for computing stellar evolution, Joss followed the development of the surface layers under various accretion rates and temperatures. He found that, for a broad range of conditions, the helium-burning shell just within the surface of the stars undergoes repeated thermal runaways accompanied by x-ray bursts that have the same general luminosities, rise times, and spectral properties as the observed bursts. Although the computed bursts do not reproduce many of the complex structures that have been observed, Joss believes that these may arise from violations of the highly symmetric conditions postulated in his model. Joss is enthusiastic about the success of his model, but he says that it still has some difficulties and will need further work.

Another class of models assumes that the bursts arise from thermal or magnetic instabilities in the accretion of matter onto a neutron star or black hole. It is not at all certain that all bursters operate by the same mechanism, and Grindlay suggests that at least some of them may involve black holes. Specifically, he has developed a model that involves thermal instabilities in the accretion of matter onto a black hole of about 10 solar masses such as could remain after the collapse of a globular cluster. This model can reproduce many of the observed properties of the bursts. Accretion instabilities can also arise for smaller objects, but do not produce the kinds of bursts usually observed. However, one burster, the "rapid burster" MXB 1730-335, produces brief, rapidly repetitive and relatively weak bursts, as well as occasional intense bursts that have the commonly observed properties. Lewin suggests[1] that the rapid bursts may be due to accretion instabilities while rarer, larger bursts are due to fusion flashes.

Although the data from the optical burst are being analyzed extremely thoroughly, everyone involved is hoping for more correlated bursts. Routine monitoring of the bursters is, however, difficult. There are many other experiments with valid claims on satellite and telescope time, and the bursters are not predictable enough for scheduling observations at useful times. Lewin's group has scheduled a total of eight weeks of observing time on SAS-3 to examine burst sources during April–July 1979. Optical observers who wish to cooperate with these observations are invited to contact Lewin or other members of the group at the Center for Astrophysics of the Massachusetts Institute of Technology.

—TVF

References

1. W. H. G. Lewin, "What are x-ray burst sources?" to be published in *Advances in Space Exploration*, vol. 3 (1979); also W. H. G. Lewin, P. C. Joss, Nature **270**, 211 (1977).
2. J. E. Grindlay, J. E. McClintock, C. R. Canizares, J. van Paradijs, L. Cominsky, F. K. Li, W. H. G. Lewin, Nature **274**, 567 (1978).
3. G. Jernigan, K. Apparao, H. Bradt, R. Doxsey, J. E. McClintock, Nature **270**, 321 (1977).
4. J. van Paradijs, Nature **274**, 650 (1978).
5. P. C. Joss, Nature **270**, 310 (1977); Astrophys. J. Lett. **225**, L123 (1978).

Two upsilon states

continued from page 17

visible. That is, the decay products tend to be emitted in two oppositely directed jets, a behavior expected from quarks. Although jetlike behavior had been observed earlier at SPEAR, the DORIS experiments show that, as expected for higher energy, the cones of the two jets become even narrower. At still higher energies, which will become available when CESR at Cornell, PETRA at DESY and PEP at SLAC start doing experiments, the study of jets is expected to provide a much better test of quantum chromodynamics. QCD assumes that each photon makes a quark and an antiquark, each of which ends up as a jet. At higher e^+e^- energies, the quark or antiquark should sometimes emit a gluon, giving rise to a three-jet event.

In the first observation of the upsilon resonances, done at Fermilab by a group from Columbia University, Fermilab and the State University of New York at Stony Brook, two or three bumps had been found[1] in the cross section for production of muon pairs in 400-GeV proton–nucleus interactions. The most recent analysis of the data, Lederman told us, gives a mass difference between the Υ and Υ' of (590 ± 35) MeV. He noted that the splitting between the J/ψ and the ψ' is 589 MeV, suggesting that the splitting for such resonances was independent of the mass of the constituent quarks.

This is contrary to various theoretical expectations based on fitting a potential model to charmonium data; these predicted $\Upsilon\Upsilon'$ splitting of about 400 MeV. The ψ resonances are assumed to be a bound state of a charmed quark, c, and its antiquark and the mass of the charmed quark to be roughly half the mass of the ψ. Similarly, the Υ resonances are assumed to be the bound state of a bottom quark, b, and its antiquark and the mass of the b quark to be roughly half the mass of the Υ.

As theorist Kurt Gottfried of Cornell recently told us, "in electrodynamics, we know the interaction of photons and electrons, and how this leads to Coulomb's law. On the other hand, in QCD we know the basic interaction between gluons and quarks. But the resulting interaction between quarks and antiquarks is not yet understood. All these potentials one uses are guesses, not theories."

DORIS results. Electron–positron storage rings are capable of giving cleaner and better resolved data on resonances like the ψ and Υ. So, accelerator specialists at DESY decided to push the total energy of the DORIS storage ring beyond its original total operating energy (8.6 GeV). By operating DORIS as a single-ring, single-bunch machine, the machine experts reached energies as high as 9.6 GeV total energy and finally more than 10 GeV. At 9.6 GeV, the PLUTO[2] and DASP-2[3] groups confirmed the existence of the Υ at (9.46 ± 0.01) GeV; they obtained a partial width for decay into e^+e^- pairs of (1.2 ± 0.2) keV, $\frac{1}{4}$ the J/ψ partial width for decay to e^+e^- pairs.

Last July DESY machine experts added additional cavities to DORIS so that the total energy was raised to more than 10 GeV, allowing the search for the Υ', but the machine did not reach an energy high enough to see the possible third bump reported by Lederman and his collaborators, at 10.4 GeV, which would correspond to Υ''.

A few days before the Tokyo conference on high-energy physics in August, the upsilon prime was detected by two groups simultaneously. A collaboration among DESY, the Universities of Hamburg and Heidelberg, and the Max Planck Institute of Physics in Munich, using the NaI Lead-Glass Detector, found[4] the Υ' to have a mass of (10.02 ± 0.02) GeV and that the mass splitting was (0.56 ± 0.01) GeV. When this precise value is imposed on the Fermilab data, Lederman told us, their Υ'' peak becomes a ten-standard deviation effect (previously a three-standard deviation effect).

The detector used by the NaI Lead-Glass Detector group has a central nonmagnetic instrument to observe the direction of charged particles; it is surrounded by sodium iodide and lead-glass detectors to measure the total energy of electrons, positrons and gamma rays. Each detector has a large angle of acceptance, covering 86% of 4π.

A collaboration of DESY with the Universities of Dortmund, Heidelberg and Lund, using the DASP-2 detector, which has an inner nonmagnetic detector covering 70% of 4π, can see both gammas and charged particles. DASP-2 has a double-arm spectrometer, too, but this device is not crucial to the Υ' experiment. The group reported[5] the same value for the Υ' mass as found in the NaI Lead-Glass Detector experiment. The DASP-2 result for the mass splitting was (555 ± 11) MeV.

The observed widths, σ, in both new DORIS experiments are roughly 9 to 12 MeV, consistent with the energy resolution of the storage ring. When the two groups reported their results at the Tokyo conference, some participants questioned how well the absolute energy could be determined when the DORIS magnets were being operated near saturation. DESY experimenters replied that they felt the absolute energy they reported was reliably determined.

By measuring the partial width for Υ and Υ' decaying into e^+ and e^- and the absolute cross section, the DORIS experimenters were also able to settle the question of the b quark's charge; it is $\frac{1}{3}$ for the b, not $\frac{2}{3}$. This second possibility had not been eliminated by the earlier Fermilab experiment because its interpretation had some model dependence, according to Lederman.

Interest in the spectroscopy of the upsilon, whose excited states are sometimes called "bottomonium," is high. A number of groups are preparing to look for these states, just as was done for charmonium, after the J/ψ and ψ' were found. As Sheldon Glashow of Harvard, who pioneered the concept of charm, recently explained to us, the behavior of the charmonium system is a very limited tool for studying the nature of the quark-quark interaction. "How fortunate we are that Nature has provided us with a fifth quark with a much larger mass as a further probe. The number of $b\bar{b}$ states that will be accessible experimentally should be considerably larger than we have already