8 February 1980, Volume 207, Number 4431 SCIENCE

Accreting Neutron Stars, Black Holes, and Degenerate Dwarf Stars

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Summary. During the past 8 years, extended temporal and broadband spectroscopic studies carried out by x-ray astronomical satellites have led to the identification of specific compact x-ray sources as accreting neutron stars, black holes, and degenerate dwarf stars in close binary systems. Such sources provide a unique opportunity to study matter under extreme conditions not accessible in the terrestrial laboratory. Quantitative theoretical models have been developed which demonstrate that detailed studies of these sources will lead to a greatly increased understanding of dense and superdense hadron matter, hadron superfluidity, high-temperature plasma in superstrong magnetic fields, and physical processes in strong gravitational fields. Through a combination of theory and observation such studies will make possible the determination of the mass, radius, magnetic field, and structure of neutron stars and degenerate dwarf stars and the identification of further candidate black holes, and will contribute appreciably to our understanding of the physics of accretion by compact astronomical objects.

Before 1971, our knowledge of the x-ray sky was extremely sketchy; x-ray photons (with energies between a few tenths of a kilovolt and tens of kilovolts) do not penetrate the atmosphere, and x-ray astronomers had perforce to rely on brief exposures, using sounding rockets and high-flying balloons for their observations. The successful launch in December 1970 of UHURU, a satellite designed for x-ray astronomical observations, followed in the decade by ten other satellites (*1*) devoted in part or entirely to x-ray astronomy, has led to 8 years of extremely rapid progress in both the observation and theory of compact x-ray sources (*2-4*). These sources, some 175 of which had been identified in our galaxy by early 1979 (*5, 6*), exhibit time variability down to the shortest time scales (~ milliseconds) thus far studied (hence the name compact) and possess luminosities, L_X, mainly in the x-ray region, up to a million times the optical luminosity of the sun (2×10^{33} ergs per second).

Observations of compact x-ray sources have served as a great stimulus to theoretical astrophysicists. Particular attention has been focused on a class of models which involve a compact object—a neutron star, black hole, or degenerate dwarf star—that is accreting matter from a nearby "normal" companion star going through a phase in its stellar evolution in which it is losing mass. The energy to produce the x-ray luminosity is largely the gravitational energy resulting from the infall of matter into the potential well of the compact star. By combining theory with observation it has proved possible to identify certain classes of compact x-ray sources with specific kinds of accreting compact objects. Thus a number of the pulsating x-ray sources have been shown to be accreting rotating magnetic neutron stars (*7*), while the bursts characteristic of many of the x-ray bursters are in all likelihood caused by runaway thermonuclear processes in matter freshly accreted on the surface of neutron stars (*8*). It is, moreover, highly likely that at least one accreting black hole, Cygnus X-1, has been discovered (*9*), while several sources have been identified as accreting magnetic degenerate dwarf stars, and characteristic signatures for their weakly magnetic counterparts have been proposed (*10*).

In nearly all these cases, one is dealing with the behavior of matter under extreme conditions not accessible in the terrestrial laboratory. More particularly, detailed studies of known or candidate neutron stars and black holes, involving combined timing, luminosity, and broadband spectroscopic observations over an extended period of time, may constitute an almost unique probe of dense and superdense hadron matter, hadron superfluidity, matter in strong gravitational fields, high-temperature plasma in superstrong magnetic fields, and the possible existence of pion condensates, neutron solids, or quark liquids in the cores of neutron stars. In this article, following a brief review of our present understanding of accretion flows toward magnetic neutron stars, black holes, and degenerate dwarf stars in binary systems, I consider the current output of the compact x-ray source "cosmic laboratory" and indicate some of the promising future avenues of investigation, with particular focus on those fundamental questions in physics which may be illuminated by such studies.

Neutron Stars, Black Holes, and Degenerate Dwarf Stars

Neutron stars and black holes are two of the end products of stellar evolution. They are believed to be formed in the gravitational collapse of aged massive stars which have reached a stage in their thermonuclear burning cycle such that

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0036-8075/80/0208-0597$02.00/0

their highly evolved, degenerate cores are no longer stable against collapse. The core [with a mass of the order of 1.4 solar masses ($M_\odot$)] and outer shells of such stars collapse until a central density which exceeds that of nuclear matter, $\rho_0 = 2.8 \times 10^{14}$ grams per cubic centimeter, is reached. As a result of the implosion, the core bounces and a shock wave is formed; if the mass, M, of the star is not too great ($8 M_\odot \leq M \leq 15 M_\odot$, say), the resulting explosion may be sufficiently powerful to drive off all or nearly all of the collapsing stellar mantle. In that case there is formed a stable neutron star, in which the gravitational attraction is balanced by the internal pressure of the (mainly) neutron liquid in its interior. Such a star is expected to have a solid outer crust, a radius of the order of 15 kilometers, and an average density comparable to ρ_0. If, on the other hand, the shock wave is not sufficiently strong to drive off the mantle, so much matter will accrete on the core that the internal pressure cannot balance the gravitational attraction, and the star collapses past the neutron star stage to a black hole. In the case of neutron star formation, and possibly also black holes, some of the energy given off in the stellar collapse will, in the form of visible light, be observable on the earth as a supernova.

Since the degenerate cores of massive stars in general rotate and possess magnetic fields, one expects that a neutron star will also. If one assumes, as a first approximation, that magnetic flux and angular momentum are conserved in the collapse, then the resulting neutron stars will possess magnetic fields of 10^{10} to 10^{13} gauss and angular frequencies of 1 to 10^3 $\sec^{-1}$ if the unstable degenerate cores, of radius $\sim 5 \times 10^3$ km, possess (not unreasonable) magnetic fields of the order of 10^5 to 10^8 gauss and angular frequencies of $\sim 10^{-5}$ to 10^{-2} $\sec^{-1}$.

An isolated neutron star with these properties will act as a pulsar; its highly conducting solid surface is subject to very large electric fields, which act to rip charged particles from it, produce a corotating magnetosphere, and lead to the acceleration of the particles and the emission of electromagnetic waves with a pulse period given by the rotational period of the star. The basic energy source or a radio pulsar is its rotational energy; as this rotational energy is converted into electromagnetic energy and charged particle acceleration as a result of the coupling of the pulsar crust to its external corotating magnetosphere, the pulsar gradually slows down (*11*).

If, on the other hand, the rotating magnetic neutron star is accreting matter from a nearby companion star, it may be visible as a pulsating x-ray star. Far from the star its magnetic field will not influence appreciably the flow of accreting matter, since it is screened out by currents induced in the infalling material. If the matter possesses sufficient angular momentum, it cannot fall directly toward the star, but rather will tend to form a disk, made up of particles gradually spiraling toward the star on Kepler-like orbits. Sufficiently close to the star, the stellar magnetic field is strong enough to force the accreting matter to corotate with the star at its angular velocity, Ω. The transition between the two regions takes place near the Alfvén surface, S_A, defined as the surface within which the accreting plasma corotates with the star. A qualitative picture of disk accretion

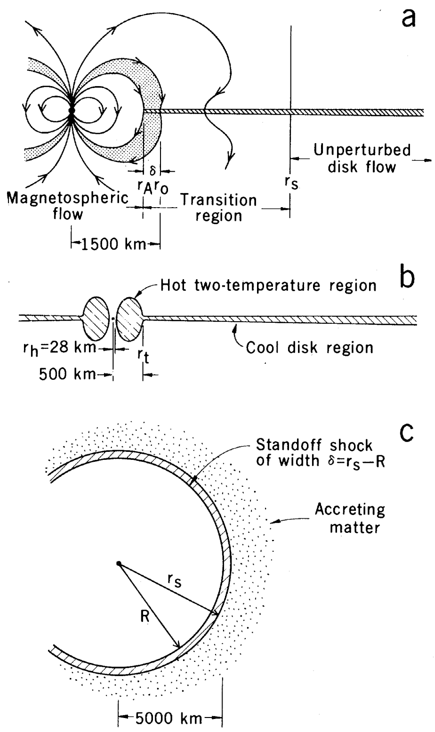

Fig. 1. (a) Schematic side view of disk accretion by a rotating magnetic neutron star [after Ghosh and Lamb (*42*)]. Beyond r_s the stellar magnetic field is completely screened, and disk flow is unperturbed by the magnetosphere. In the transition region between r_s and r_A, the disk flow changes into magnetospheric flow. In the outer transition zone, from r_s to r_o, viscous stresses dominate magnetic stresses; in the boundary layer, δ, magnetic stresses dominate. (b) Schematic side view, to the same scale as (a), of disk accretion by a black hole of mass $\sim 10\ M_\odot$, under the assumption that a hot bloated two-temperature disk forms between r_h, the event horizon, and r_t, the boundary, beyond which one finds a cool, optically thick disk [after Eardley and co-workers (*18*)]. (c) Schematic view of spherical accretion by a degenerate dwarf of radius R [after Kylafis *et al.* (*10*)], showing a standoff shock, of width $\delta << R$, which forms at r_s. The scale is one-fifth that in (a) and (b).

onto a magnetic neutron star is shown in Fig. 1a. With neutron star magnetic moments in the expected range of 10^{29} to 10^{32} gauss-cm^3 and characteristic x-ray luminosities $\sim 10^{35}$ to 10^{37} erg/sec, the Alfvén surface typically is found at a distance, r_A of $\sim 10^8$ cm, large compared to the neutron star radius, R. As a result, matter which is threaded onto stellar field lines near S_A will, in the case of a dipolar field, be strongly channeled by the field toward the magnetic poles of the star; there it forms hot spots of area $\lesssim \pi R^2(R/r_A) \sim 1$ km^2 near which the gravitational energy of the infalling matter (protons colliding with the stellar surface arrive with an energy per particle of order ~ 100 million electron volts) is released (*12, 13*). The resulting radiation emerges from the neighborhood of the stellar surface in a strongly anisotropic angular pattern which depends on the details of the accretion process; for an oblique rotator (a star for which the magnetic field is not aligned with the axis of rotation), one has a natural mechanism for the production of pulsed radiation with a temperature in excess of 6 kiloelectron volts (*12, 14*). Unlike the radio pulsar, such sources will, on average, tend to spin up as a result of the torque transmitted to the star by the accreting matter (*12, 15*).

Because no radiation can escape its intense gravitational field (hence the name black hole), a black hole in isolation is not observable. Its properties (mass M, angular momentum J, charge Q) can, in principle, be determined by their effect on matter which is accreting onto it or, in the case of its mass, through the influence of its gravitational field on other stars in its vicinity. X-rays offer an extremely valuable diagnostic tool for the identification of a possible black hole, because matter on the verge of falling into a black hole (that is, disappearing within its event horizon, from which no radiation can escape its superstrong gravitational field) of 5 to 15 $M_\odot$, say, is expected to emit radiation in the x-ray region which displays chaotic time variability on a scale as short as 1 msec.

Theoretical work on models of accretion onto black holes has tended to concentrate on disk accretion, although the possibility cannot be ruled out that in Cyg X-1, the most promising black hole candidate, one is observing unsteady spherical accretion (*16*). Our understanding of the behavior of disks is still comparatively primitive, since we lack detailed calculations of disk viscosity, which controls the motion of matter as it spirals inward, and must rely instead on phenomenological models (*17*) invoked to explain the behavior of Cyg X-1. One of these, due to Eardley and co-workers (18) is illustrated in Fig. 1b, where one sees a hot, bloated two-temperature region extending down to the event horizon at r_h, joined smoothly to a thin cool-disk region [$r_h = \delta(GM/c^2) \sim 1.5\delta(M/M_\odot)$ km, where G is the gravitational constant, c is the speed of light, and δ is a number from 2 to 6, depending on the angular momentum of the black hole (19)]. The observed power-law hard x-ray spectrum, extending to beyond 100 keV, originates in the hot (electron temperature $T_e \sim 2 \times 10^9$ K) optically thin plasma near the black hole, with multiple inverse Compton scattering of soft photons (produced in the cool outer disk) against the electrons present there being a likely emission mechanism. Occasionally, Cyg X-1 undergoes transitions to a "high state," in which a new strong softer x-ray component (< 7 keV) appears, which could well originate in the replacement of the optically thin disk near the black hole by an optically thick accretion disk, characterized by $T \lesssim 6 \times 10^6$ K and $R \gtrsim 50$ km (18).

Chaotic rapid time variability has been viewed as a likely signature of a black hole; qualitative explanations for its appearance include hot spots (clumps of matter in the disk) and Compton echos—time-dependent spectral variations associated with disk matter (18). However, in common with other suggested x-ray signatures based on observations of Cyg X-1 (the hard power law spectrum, the existence of linear polarization at a level of a few percent), it is probably not unique to a black hole, but could be present in an accreting rotating nonmagnetic neutron star (20). Thus at present it remains a highly useful signal flag; further progress in identifying a black hole prospect requires optical identification of its binary companion and, through combined optical and x-ray observations of the binary system, the ability to place a lower limit on the mass of the candidate black hole which is in excess of the maximum mass ($\sim$ 2 to 5 $M_\odot$) of a neutron star. In this way, the compact x-ray source Cyg X-1 has emerged as the most promising (and, as of this writing, the only really good) black hole candidate. It has been shown to possess a mass $\gtrsim 6$ $M_\odot$, provided it lies in a binary system, while the parameter space available for the alternative observational possibility—that it possesses a mass $\sim M_\odot$ and is part of a triple system—has been steadily reduced (16).

Degenerate dwarf stars, in which the gravitational attraction is balanced by the internal pressure of the degenerate electrons (electrons in a temperature and density regime such that quantum effects, as manifested in their degeneracy required by Fermi-Dirac statistics, play an important role), represent the third class of stable compact astronomical objects. When cold, such stars have a maximum mass of ~ 1.4 $M_\odot$, possess radii of $\sim$ 5000 km, and, as noted, may have magnetic fields up to 10^8 gauss. Accreting degenerate dwarfs form an important class of galactic x-ray sources. A qualitative picture of spherical accretion onto a degenerate dwarf is shown in Fig. 1c; as the accreting matter flows toward the star, a strong shock is formed, with a jump in the temperature and density of the infalling matter at the shock radius, r_s. Within r_s, the hot postshock matter gradually cools and comes to rest at the stellar surface of radius R (21, 22). If the star possesses a strong magnetic field ($10^6 \lesssim B \lesssim 10^9$ gauss, say) the matter will be channeled toward the magnetic poles of the star and will only accrete onto some fraction, $f << 1$, of the stellar surface (22, 23). The characteristics of the emitted radiation depend in general on the accretion rate (or what is equivalent, the luminosity), on B, and on f; recent quantitative theoretical work is reviewed below.

It should be emphasized that in all three cases, accreting neutron stars, black holes, and degenerate dwarfs, one is faced with the challenging problem of constructing a self-consistent solution for the emission region, where there is significant coupling between the emerging radiation and the accreting plasma. Some of the physical processes which must be taken into account in order to realize this goal are described, for the case of neutron stars and degenerate dwarfs, in the following sections.

Accreting Neutron Stars

Understanding the physics of accreting neutron stars presents a formidable challenge to both the theorist and the observer; at each stage in the accretion process there are a number of plausible physical alternatives which must be considered in some detail in order to determine their relevance for a particular compact x-ray source. Thus, far from the star one seeks to understand the physics of accretion flows: Is the star being fed by an accretion disk or by a stellar wind, analogous to the solar wind of accelerated plasma found in our own solar system? For a magnetic neutron star, the large-scale structure of the magnetosphere (such questions as where the stellar magnetic field begins to influence the flow of accreting plasma, and where the Alfvén surface is) depends in turn on the nature of the accretion flow, as well as on the stellar magnetic moment, μ, and rotational period, P. Plasma in the vicinity of the magnetospheric boundary is subject to magnetic, viscous, and matter stresses, which determine the torque exerted by the accreting matter on the star, while the physical conditions present there determine how plasma enters the magnetosphere. Does it become threaded by the stellar field [for example, as a result of tearing-mode instabilities at neutral points in the magnetic polar regions (12)] or does it penetrate the magnetosphere between field lines because the magnetosphere becomes Rayleigh-Taylor unstable as a result of the accumulation of plasma at its boundary (24, 25)? How plasma enters the magnetosphere in turn determines the x-ray pulse shape. If the plasma becomes threaded by the field lines near the magnetospheric boundary far from the stellar surface, channeling by a dipolar field will lead to x-ray emission localized at the magnetic poles and an observed single or double pulse, while if the field structure is more complex, and matter becomes threaded by field lines well within the magnetospheric boundary, considerably more complex pulse shapes are to be expected (24).

A quantitative investigation of disk accretion by rotating magnetic neutron stars has been carried out by Ghosh and Lamb (26), who use two-dimensional hydrodynamic equations to study the interaction between the stellar magnetic field and the accreting plasma at the magnetospheric boundary. The basic physical picture to which they are led is shown in Fig. 1a; they find that as a result of turbulent diffusion, magnetic field reconnection, and the Kelvin-Helmholtz instability, there will be a broad transition region between the outer region of the disk, in which the flow of matter screens out the stellar field, and the radius $r_{co} \sim r_A$ inside which the plasma is forced by the stellar field to corotate with the star. In most of the transition region the viscous stresses dominate the magnetic stresses and the flow is nearly Keplerian, but in the inner part, or boundary layer, where the magnetic stresses dominate, the disk flow departs significantly from its Keplerian value.

Thus far we possess only a qualitative understanding of the basic x-ray emission mechanism. Does the infalling material penetrate directly into the surface layers of the star (12, 27), or is a shock formed above the stellar surface which

Table 1. Observational and theoretical parameters of nine pulsating x-ray sources [from Ghosh and Lamb (*42*)].

Source	P (seconds)	L_{37}*	T_s (years)	μ_{30}†	r_o (10^8 cm)	$\Omega/\Omega_K(r_o)$
SMC X-1	0.71	50	$1.3 \pm 0.4 \times 10^3$	0.50	0.36	0.11
Hercules X-1	1.24	1	$3.3 \pm 0.6 \times 10^5$	0.47	1.1	0.35
4U 0115+63	3.6	$\gtrsim 0.9$	$\sim 3.1 \times 10^4$	1.4	2.0	0.30
Centaurus X-3	4.84	5	$3.6 \pm 0.6 \times 10^3$	4.5	2.4	0.29
A 0535+26	104	6	29 ± 8	3.3	1.9	9.7×10^{-3}
GX 1+4	121	4	50 ± 13	0.93	1.1	3.4×10^{-3}
Vela X-1	283	0.1	$1.0 \pm 0.4 \times 10^4$	86	40	0.35
GX 301-2	700	0.3	120 ± 60	0.3	1.2	6.7×10^{-4}
Perseus X-1	836	4×10^{-4}	$5.9 \pm 1.5 \times 10^3$	4.8	38	0.10

*L_{37} is the luminosity, in ergs per second, divided by 10^{37}. †For each source, Ghosh and Lamb adjust the stellar magnetic moment, measured in units of 10^{30} gauss-cm^3, to obtain the best possible agreement between the observed value of T_s and their theoretical value for a 1.3 $M_\odot$ star whose radius and inertial moment are taken to be those obtained by Pandharipande *et al.* (*43*), using a stiff (TI) equation of state. The magnetic moments of all sources except Vela X-1, which is possibly a wind-fed source, lie within an order of magnitude of one another.

can, in the case of an unmagnetized star, give rise to a very hard spectrum which extends up to γ-ray energies (*28*)? Where channeling by a strong magnetic field leads to formation of an accretion column, electron cyclotron emission may produce a broad spectral feature (*29, 30*), while interaction of the emerging radiation with the accreting matter in the column can give rise to significant cyclotron absorption features (*24, 31*). The resulting beam may be fan-shaped or pencil-shaped, depending on whether the radiation is scattered out of the accretion column, and since that scattering depends on both the field strength and the energy of the scattered x-rays, changes in the pulse shape with energy, and possibly phase, are to be expected (*12, 32*).

The gravitational energy released per unit mass of matter falling on the surface of the star exceeds that produced by nuclear burning of the newly accreted matter by more than an order of magnitude. However, nuclear burning of the newly accreted matter will occur in a very thin series of thermonuclear burning shells in the stellar envelope [the scale height is in meters because of the large value of the gravitational acceleration g ($\sim 10^{11}$ that on the earth) at the surface of a neutron star]. One of these shells may become unstable, producing a thermonuclear flash involving the sudden release of an amount of energy large compared to the steady surface emission (*33*); if this energy is transported rapidly outward to the surface of the star, it will be released from the photosphere of the star as an x-ray burst (*34*). The detailed numerical calculations of helium-burning flashes which have thus far been carried out (*35*) yield results which are in good qualitative agreement with observations of the so-called type I bursts, which come in intervals of hours to days, exhibit spectral softening during burst decay, and are emitted by all burst sources (*8*). On the other hand, an accretion instability (*36*) seems to be the most likely origin of a second class of bursts, which occur on time scales of seconds to minutes, exhibit no spectral softening, and are emitted by MXB 1730-335, the so-called rapid burster (*8*).

Finally, as we shall see in more detail in the following sections, the radius, inertial moment, internal structure, and dynamic response of the neutron star may influence x-ray observations. Since, for a given mass, these are sensitive to the equation of state of the superdense hadron matter found in the stellar interior, and since for many of the pulsating x-ray sources the mass of the neutron star is directly observable, understanding the behavior of accreting neutron stars may lead to a greatly increased understanding of the states of matter within neutron stars as well as their magnetospheric and surface properties.

Period Variations in Pulsating X-ray Stars

Most, and perhaps all, of the 16 pulsating x-ray sources so far discovered (*6*) are accreting rotating magnetic neutron stars in close binary systems. Studies of period variations in these sources represent an especially valuable tool for investigating neutron star properties. X-ray observations of the Doppler shift of the period, when combined with optical observations of the companion star, yield information on neutron star masses (*37*). The best determined neutron star mass from x-ray observations is that of Hercules X-1, for which Middleditch and Nelson (*38*) obtain 1.3 ± 0.1 $M_\odot$ from an analysis of optical pulsations (*39*). The masses of the other four stars for which mass determinations have been made are not known as well (Centaurus X-3, 1.9 ± 1.2 $M_\odot$; SMC X-1, 1.1 ± 0.6 $M_\odot$; Vela X-1, 1.7 ± 0.3 $M_\odot$; and 4U1538-52, 1.9 ± 1.1 $M_\odot$) (*37*), primarily because a 10 percent uncertainty in the difficult-to-measure orbital velocity curves can lead to an uncertainty in the neutron star mass of order 1 $M_\odot$. There exists the possibility that all these neutron stars have approximately the same mass (~ 1.4 $M_\odot$); Taylor *et al.* (*40*) have shown that if the binary pulsar consists of two neutron stars (and definitive evidence is still lacking on this point), then both have masses of 1.39 ± 0.15 $M_\odot$.

Secular changes in the period have been measured for nine sources, all of which have been observed to spin up on time scales $T_s \equiv P/\dot{P}$ which range from 50 to 3.3×10^5 years. The good qualitative agreement between the observed values of T_s and those calculated for accreting magnetic neutron stars (*12, 15*), together with the clear disagreement of the observations and expected spin-up torques for accreting degenerate dwarfs, has been a key element in the identification of these sources as accreting magnetic neutron stars (*12, 41*).

In the case of disk accretion, Ghosh and Lamb (*42*) have carried out detailed calculations which take into account the appreciable magnetic coupling they find between the star and the accreting plasma in the outer part of the disk. For "slow" rotators, characterized by stellar angular velocities Ω small compared to $\Omega_K(r_o)$, the Keplerian angular velocity at r_o, the outer edge of the boundary layer, this magnetic coupling acts to enhance by some 40 percent the accretion torque which acts to make the star spin up. For "fast" rotators, characterized by $\Omega \gtrsim \Omega_K(r_o)$, the torque on the star due to magnetic coupling in the outer part of the disk opposes that due to the coupling of the plasma and magnetic field at the inner edge of the disk, so that such sources spin up on a much longer time scale. Indeed, for sufficiently high stellar velocities—or what is equivalent, sufficiently low accretion rates [causing $\Omega_K(r_o)$ to decrease]—the star will spin down even while accretion continues. In this way, Ghosh and Lamb are able to explain the existence of an anomalously large number of long-period sources with relatively short spin-up times as resulting from recurrent "low" states during which the accretion rate is much reduced, so that the star is frequently subject to strong spin-down torques.

The results obtained by Ghosh and Lamb for the nine pulsating x-ray sources for which secular spin-up has been observed are given in Table 1. The fact that they are able to obtain quantitative agreement between theory and observation using a "standard" neutron star [a 1.3 $M_\odot$ star whose radius and inertial moment are taken to be those calculated by Pandharipande *et al.* (*43*) with a "stiff" (TI) equation of state (see below)] and a narrow range of magnetic moments ($0.5 \lesssim \mu_{30} \lesssim 5$), for all sources except Vela X-1, strongly suggests that these stars, despite their widely varying periods and luminosities, are all magnetic neutron stars accreting from Keplerian disks. The large magnetic moment calculated for Vela X-1 suggests that it might be a wind-fed source, in which case one would obtain the observed spin-up rate with μ_{30} in the above range (*42*).

Valuable information about accretion flows and neutron star structure may also come from the irregular short-term (~ days to months) period variations which have been observed in the four pulsating x-ray sources (Her X-1, Cen X-3, Vela X-1, and Perseus X-1) whose period variations have been studied in some detail (*44*). Lamb *et al.* (*45*) suggested that such variations could arise from fluctuations in the external torque on the stellar crust, associated with large- or small-scale variations in the accretion flow, or from internal torque variations, associated with oscillations of the fluid core or the unpinning of vortices in the inner crust of the star (see below). They developed a statistical description of the torque variations in terms of noise processes, and showed that a power spectrum analysis of the observed angular velocity variations not only would test the validity of the statistical description, but could provide information as well on accretion flows and the internal structure of neutron stars, including the relative inertial moments of the crust and the superfluid neutron core, the crust-core coupling time, and the frequencies of any low-frequency internal collective modes. The theory has recently been shown to apply to Her X-1 by Boynton and Deeter (*46*), with results which I shall discuss below.

Regular short-term period variations have been seen in one pulsating x-ray source [Her X-1, which has a well-defined 35-day periodicity (*47*)] and may exist in others. An appealing possibility is that the clock mechanism for such variations is stellar wobble. Because neutron stars are oblate and possess a solid outer crust, they may execute a free precession mode analogous to the Chandler wobble of the earth. The wobble period of a neutron star reflects both its structure and its evolutionary history (*48*). To the extent, therefore, that comparatively large-amplitude stellar wobble may be shown to exist in pulsating x-ray sources (*49*) (an unambiguous identification of the clock mechanism has not yet proved possible for the 35-day periodicity of Her X-1), valuable information about the internal structure of a neutron star and its evolutionary history may be obtained (*43*).

Degenerate Dwarf X-ray Sources

The physical conditions expected for the hot postshock plasma formed near the surface of an accreting magnetic degenerate dwarf ($T \sim 10$ keV, $\rho \gtrsim 10^{-10}$ g/cm^3, $B \gtrsim 10^6$ gauss) resemble those found in magnetically confined plasma fusion experiments, with one significant difference. Because the depth of the emission region is some 100,000 times greater (100 km compared to 1 m, say), it is necessary to calculate the electron cyclotron emission radiation at very high harmonics (up to order 50) of the fundamental frequency, eB/mc (where e and m are the charge and mass of the electron), in order to take into account properly the effects of self-absorption (optical depths at the fundamental being as large as 10^9). Quantitative calculations in this uniquely astrophysical regime have recently been carried out by Lamb and Masters (*50*) under the assumptions that the accreting matter is fully ionized and that the emission region is a geometrically thin slab of uniform temperature and density. (The latter is a not unreasonable idealization as long as the physical conditions are such that the depth of the slab, d, is small compared to its width, $\sim\sqrt{2f}\,R$.)

Lamb and Masters find that the resulting emitted radiation may be expected to consist primarily of three distinct components. Two of these, cool electron cyclotron radiation, typically in the ultraviolet, and hot bremsstrahlung radiation resulting from electron-ion collisions, typically in the hard x-ray region (10 to 100 keV), originate in the hot postshock emission region, while the third, blackbody (BB) radiation in the hard ultraviolet or soft x-ray region, is produced by the absorption and reemission at the stellar surface of this cyclotron (Cyc) and bremsstrahlung (Brem) radiation. One therefore expects $L_{BB} \sim L_{Cyc} + L_{Brem}$. They predict that magnetic dwarfs can be very strong ultraviolet sources (< 10 eV), so strong that the luminosity observed in the x-ray region may be only a few percent of the total accretion luminosity—only "the tip of the iceberg." Moreover, they find that the position and relative strengths of the spectral components vary markedly with magnetic field and with changes in the accretion rate, so that observation of qualitative features of the spectrum may be sufficient to determine the field strength of a source, while study of changes in that spectrum with luminosity should provide a sensitive observational test of the theoretical calculations and lead to a determination of both the stellar mass and the accretion rate.

At present, it appears likely that there are at least three distinct classes of accreting magnetic degenerate dwarfs: sources in which the rotation period of the star is synchronized with the orbital period of the binary system, of which AM Herculis is the prototype; sources whose rotation period is not synchronized with the binary period, which also show clear evidence of an accretion disk, of which DQ Herculis is the prototype; and cataclysmic variable sources, of which SS Cygni is the prototype, which resemble AM Her objects in some respects, but which show strong optical evidence for a disk (*51*). The latter class display irregular outbursts, associated with episodic accretion; the presence of significant magnetic fields (inferred from their similarity to AM Her objects) may disrupt the disk and lead to radial inflow near the star. The AM Her objects thus serve both as an excellent proving ground for theory [for instance, Lamb (*51*) infers a magnetic field of $\lesssim 3 \times 10^7$ gauss from his analysis of ultraviolet as well as soft and hard x-ray observations] and as a guide to developing a better physical picture of the SS Cyg objects, the further study of which should lead to valuable information concerning accretion flows in the presence of magnetic fields. Objects in the DQ Her class offer a further opportunity for such studies, and hold out the promise, through careful timing studies, of learning about the internal structure of degenerate dwarfs from noise measurements, in a fashion directly analogous to that considered above for accreting magnetic neutron stars.

The spectra calculated for accretion onto nonmagnetic or weakly magnetic degenerate dwarfs by Kylafis and Lamb (*52*) differ primarily from those for the strongly magnetic dwarf stars in the absence of the strong ultraviolet cyclotron radiation associated with magnetic fields of $\gtrsim 10^6$ gauss; in other words, $L_{Cyc} << L_{Brem}$. For both types of stars, Compton scattering of photons against electrons may play an important role; when the accretion rate is sufficiently large the bremsstrahlung radiation produced in the postshock plasma may be degraded by Compton scattering against the electrons present there, while secondary radiation produced by Compton heating of the electrons present in the infalling matter above the shock may also play a role. For the nonmagnetic dwarfs, the blackbody component produced by the bremsstrahlung photons that are absorbed by the stellar surface and then reemitted will lie in the soft x-ray region.

Kylafis and Lamb find that at moderate and high accretion rates, the spectra exhibit a high-energy tail and that, as a consequence of the Compton scattering, there is a striking correlation between x-ray spectral temperature and the luminosity of the source, a correlation which is expected to provide a signature for accreting nonmagnetic degenerate dwarfs. Such spectral changes with luminosity were observed by Branduardi (*53*) in Cyg X-2, and through comparison of theory and observation, Branduardi *et al.* (*54*) conclude that Cyg X-2 is an accreting degenerate dwarf with a mass of 0.4 $M_\odot$, located at a distance of 250 ± 50 parsec. On the basis of his theoretical calculations with Kylafis, Lamb (*51*) has called attention to the fact that while not all the hitherto unidentified galactic bulge or Scorpius X-1-like sources (so called because of their location and similarity in spectral behavior to Sco X-1) can be accreting nonmagnetic degenerate dwarfs because their intrinsic luminosities are too large (Kylafis and Lamb find $L_{\max} \sim 4 \times 10^{36}$ erg/sec, almost an order of magnitude greater than had been hitherto expected), a number of these sources exhibit a pronounced correlation between spectral temperature and x-ray luminosity, and hence must be regarded as candidate accreting nonmagnetic degenerate dwarfs. He concludes that the total number of such objects in our galaxy may be $\sim 10^4$, which is to be compared to an estimated number of strongly magnetic accreting dwarf sources of $\sim 10^6$, and some 100 bright ($L_x \gtrsim 10^{36}$ erg/sec) accreting neutron star x-ray sources.

Neutron Stars as a Hadron Physics Laboratory

Extensive theoretical studies have shown that neutron stars with a mass of $\sim 1.4\ M_\odot$ have radii of the order of 10 to 16 km; a solid outer crust $\sim$ 1 to 5 km thick containing increasingly neutron-rich nuclei in a periodic array, free electrons, and free neutrons; and a liquid interior that begins at densities somewhat less than ρ_0 and contains largely superfluid neutrons. The behavior of neutron

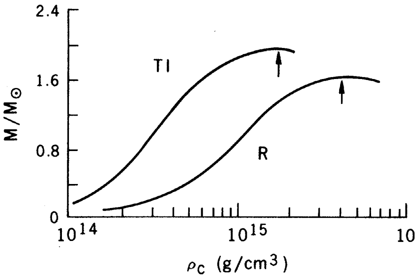

Fig. 2. Neutron star mass as a function of central density for models of the neutron-neutron interaction leading to soft (*R*) and stiff (*TI*) equations of state. The arrows indicate the maximum mass and central density.

star matter in the crustal region is comparatively well understood (*55*); the remaining and key ingredient in determining the maximum mass and internal structure of neutron stars is the calculation of a reliable equation of state for the neutron liquid phase. It is a difficult calculation, in part because the basic interaction between neutrons is still not perfectly known, in part because, for a given interaction model, calculation of the ground state energy for a system at nuclear densities and beyond is a far from trivial many-body problem (*56*).

Pandharipande *et al.* (*43*) have shown that one can construct a variety of models for the neutron interaction which are consistent with terrestrial constraints (the free nucleon scattering data and the experimentally known energy, equilibrium density, and symmetry energy of nuclear matter). The theoretical possibilities for the resulting equation of state span a range from "soft" equations of state (derived from models for which the average system interaction energy is attractive at nuclear densities) to "stiff" equations of state (derived from models for which the average system interaction energy becomes repulsive at subnuclear densities). Representative examples of the corresponding models are the phenomenological Reid (R) potential for neutron-neutron interaction (*57*) and the tensor interaction (TI) model, which assumes that the attractive part of the neutron-neutron interaction comes from higher order pion exchange (*58*). Mass versus central density curves calculated for these two models are shown in Fig. 2, while cross sections of corresponding stars of 1.4 $M_\odot$ are shown in Fig. 3. There one sees that to the extent that properties such as the mass, the stellar radius, and the ratio of the moment of inertia of the solid outer crust, I_c, to the total inertial moment, I, can be directly determined from observation, it is possible to reach conclusions concerning a matter of such fundamental importance in physics as the basic interaction between hadrons on the basis of astronomical observation alone.

If the equation of state is comparatively stiff, the central density of a star as massive as 1.4 $M_\odot$ is less than twice ρ_0, while even the most massive stars possess central densities of $\sim 10^{15}$ g/cm^3. It is unlikely that one will find in the cores of such neutron stars some of the exotic forms of matter which have been conjectured to exist there, such as quark matter or abnormal matter (*59*). Indeed, if something close to TI turns out to be the correct interaction model, then neither pion condensation nor the formation of a neutron solid core, both of which have been suggested to begin at densities of the order of twice ρ_0 (*59, 60*), are likely to occur in stars of $\sim 1.4\ M_\odot$, and may not occur in nature at all if the process of neutron star formation tends to favor stars of this mass. On the other hand, if the equation of state is a good deal less stiff than, say, the TI model, pion condensation may occur and act to further soften the equation of state. Two possibilities of this sort are considered by Baym and Pethick (*61*), who find the resulting maximum stellar mass is $\sim 1.5\ M_\odot$, corresponding to a central density of $\sim 6 \times 10^{15}$ g/cm^3. It should further be noted that all present microscopic calculations of the equation of state of neutron matter lead to stars whose maximum mass is $\lesssim 2\ M_\odot$, well below the $\sim 5\ M_\odot$ limit obtained by Hartle (*62*) using only general continuity and causality arguments.

The likelihood of hadron superfluidity in nuclei was first considered by Bohr *et al.* (*63*), who applied the (then) newly developed microscopic theory of superconductivity of Bardeen, Cooper, and Schrieffer (*64*) to nuclear matter and finite nuclei. Because the fundamental interaction between hadrons is attractive at long distances, the BCS pairing mechanism leads to the formation of a macroscopically occupied condensate, with energy gaps (and transition temperatures) which may be as large as several million electron volts. Hence at the comparatively low temperatures ($\lesssim$ kiloelectron volts) expected for all but newly formed neutron stars, one expects conditions to be favorable for hadron superfluidity.

At least three distinct hadron superfluids are expected inside neutron stars:

1) In the inner part of the crust (corresponding to densities $4.3 \times 10^{11} \lesssim \rho \lesssim 2 \times 10^{14}$ g/cm^3), the free neutrons, which coexist there with the neutron-rich nuclei, probably form a $^1S_0$ paired superfluid. Because the star is rotating,

the neutron superfluid will not be spatially uniform; instead it will contain an array of vortices, parallel to the axis of rotation of the star, each having quantized circulation $h/2m$, where h is Planck's constant, and m is the neutron mass (*65*). The cores of the vortices, where the condensate wave function decreases to zero, may be pinned to the crustal nuclei or may thread the spaces between them. Whether such pinning occurs in some portions of the crust depends on whether it is energetically favorable for the "normal" core region in the neutron superfluid to coincide with the crustal ions; where the coherence length in the neutron superfluid is comparable to the size of the nuclei, conditions are favorable for pinning (*66*). Recent calculations (*67*) suggest that pinning will take place throughout much of the inner crust.

2) In the quantum liquid regime ($\rho \gtrsim 2 \times 10^{14}$ g/cm^3), where the crustal nuclei have dissolved into free neutrons and protons, the neutron superfluid is likely in a $^3P_2$ paired state (*68*) containing a vortex array.

3) The protons in the quantum liquid interior are expected to be superconducting, again in consequence of the strong attractive hadron-hadron interaction. They corotate with the electrons present there (since any differential rotation would produce extremely strong magnetic fields and hence cost a great deal of energy), and both protons and electrons may be expected to corotate with the nuclei and electrons in the crust, since the strong magnetic field inside the star is tied to the charged particles in both the crust and the interior (*69*).

Hadron superfluidity has a number of possible observational consequences for pulsating x-ray sources. If both the neutrons and protons in the liquid interior are superfluid, the coupling between the normal outer crust and the interior superfluid neutron liquid is so weak that macroscopic times (~ days to years) may be required for the two parts of the star to come to equilibrium (*70*). Such a dynamic response had been observed following sudden spin-ups of the Crab and Vela pulsars and provides evidence for hadron superfluidity in these pulsars (*71*). It may also be observable in the power spectrum of frequency variations in pulsating x-ray sources. Thus, Lamb *et al.* (*45*) have shown that in the absence of internal modes with a frequency in the range covered by a power spectrum analysis of the fluctuations in the angular velocity of the crust, one expects to find a shoulder in the power spectrum at frequencies $\omega \sim 1/\tau$, where τ is a characteristic relaxation time. At low frequencies ($\omega\tau << 1$) the star responds to any torque variation like a rigid body of inertial moment I, since the crust shares any change in its angular momentum with the superfluid neutrons in a time τ which is short compared to the time scale for changes in the torque; on the other hand, at high frequencies ($\omega\tau >> 1$), the crust has no time to share its angular momentum with the core, and will instead respond like a rigid body of moment of inertia I_c, with the consequence that the fluctuation level is reduced by a factor of $(I_c/I)^2$.

Identification of glitches or noise processes originating in the vorticity jumps of the pinned neutron superfluid would provide evidence for both the pinning mechanism and the presence of neutron superfluid in the inner crust. Another possibility is the direct observation of a Tkachenko (*72*) mode, a collective shear mode of the vortex lattice in the interior neutron superfluid. The period of such a mode with a wavelength comparable to R is $\sim 2R\sqrt{P}$ months (for R in kilometers and P in seconds), so that Tkachenko modes with a period of the order of months can, in principle, be excited by the accretion torque acting on a pulsating x-ray source.

Neutron Star Properties from X-ray Observations

The extent to which it has proved possible to determine properties of neutron stars from observations on compact x-ray sources is summarized in Tables 2 and 3. Some brief comments follow.

Measuring neutron star magnetic fields. The spectra of pulsating x-ray sources can provide information about the strength of the magnetic field near the stellar surface, whereas measurements of secular period changes provide information about the dipole component of the surface magnetic field. The observation by Trümper *et al.* (*29*) of a feature in the pulsed high-energy spectrum of Her X-1, and by Wheaton *et al.* (*73*) of a comparable feature in the pulsed spectrum of 4U0115-63 has been interpreted as indicating the existence of surface fields of some 4×10^{12} to 6×10^{12} gauss in Her X-1 (depending on whether the feature is ascribed to cyclotron emission or absorption) and $\sim 2 \times 10^{12}$ gauss in 4U0115-63. These values may be compared with the fit which Ghosh and Lamb obtain for the observed spin-up torques for these pulsating sources: $\mu_{30} \sim 0.5$ for Her X-1 and $\mu_{30} \sim 1.4$ for 4U0115-63. Taken together, these results suggest that there are important nondipolar magnetic fields in these neutron stars.

Neutron star structure and dynamics from an analysis of period variations. Boynton and Deeter (*46*) do not find structure in the power spectrum of the angular velocity variations of Her X-1, from which they conclude that either $I_c \gtrsim I/2$ (a likely possibility, since $I_c \simeq I/2$ for a 1.4 $M_\odot$ star), or the crust-superfluid coupling time is shorter than 1 day or longer than 10^2 days.

Neutron star surface temperatures.

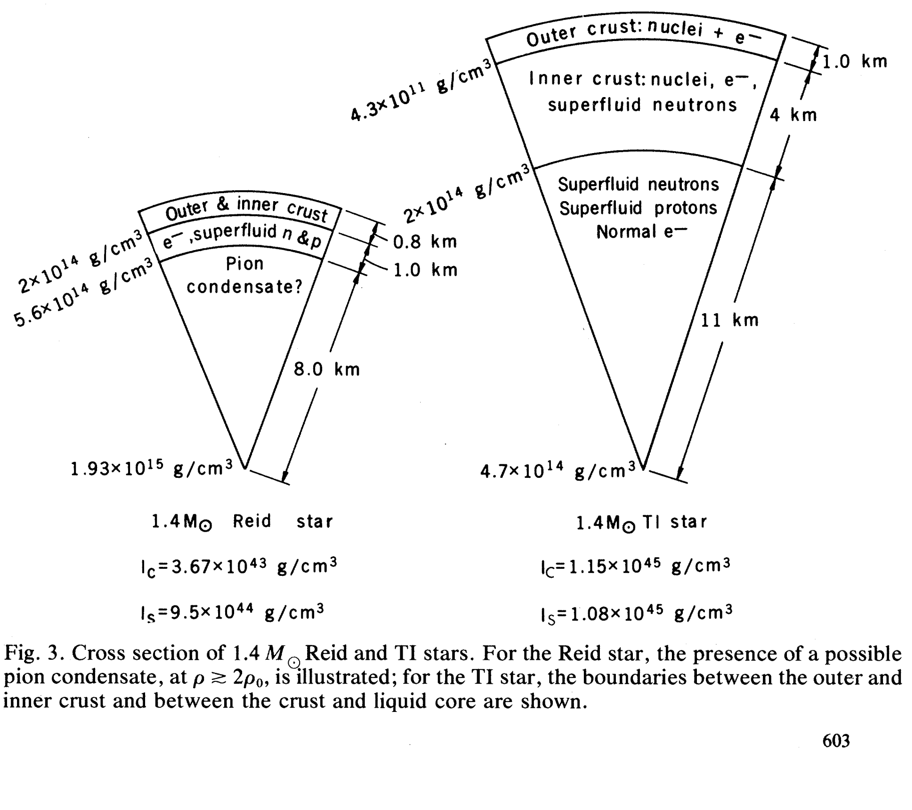

Fig. 3. Cross section of 1.4 $M_\odot$ Reid and TI stars. For the Reid star, the presence of a possible pion condensate, at $\rho \gtrsim 2\rho_0$, is illustrated; for the TI star, the boundaries between the outer and inner crust and between the crust and liquid core are shown.

Measurements of the surface temperature of neutron stars of known age (associated with a historical supernova, or supernova remnants of otherwise known age) can, in principle, provide valuable information about the states of matter and physical processes in the stellar interior which control the cooling of stars following their initial formation, as well as place limits on any internal dissipative processes which might act to heat a star. Thus far no observations of steady blackbody emission from a neutron star have been made, although many attempts have been made to detect such radiation from the Crab pulsar and upper limits on this emission have recently been obtained for a number of other candidate neutron stars by investigators using HEAO-2 (see Table 3). As has recently been emphasized (*74, 75*), our current theoretical understanding of neutron star cooling (*61*) is such that no definitive conclusions can yet be drawn from these observations concerning the states of matter (that is, pion condensates) and physical processes in the interior of these stars.

Neutron star radii from x-ray bursters. The shape of the x-ray spectrum in the tail of many observed x-ray bursts can be fit, to first approximation, by a blackbody spectrum with a decreasing temperature, a result which suggests that one is observing radiation from a cooling surface of constant size (*76*). Van Paradijs (*77*) has analyzed SAS-3 observations of x-ray bursts from ten sources and finds a striking uniformity in their properties. He concludes that if the peak luminosity in each burst is a standard candle, the size of the cooling surface is approximately the same for these burst sources. With the further assumptions that the peak luminosity corresponds to the Eddington limit, $L_E = 1.25 \times 10^{38}$ $(M/M_\odot)$ erg/sec, for a 1.4 $M_\odot$ star [a result which is roughly consistent with the calculations of Joss (*35*) for a helium-burning flash in the surface layers of an accreting neutron star] and that x-ray bursters are located symmetrically about the galactic center at a distance of ~ 9 kiloparsecs, he finds the radius of the emitting region to be 8.5 ± 1.5 km (*77*). Although bursters have not been shown definitely to be neutron stars, these results provide strong circumstantial evidence that they are. The radius obtained by van Paradijs is likely an underestimate of the radius for neutron stars of this mass, since strong magnetic fields, if present, might constrain the emission region to be less than the entire surface (*4*), while recent calculations suggest that the influence of electron scattering on the radiative opacity of the outer surface layers of the star could lead to an underestimate of the radius of the emitting region by as much as a factor of 2 (*78*).

Is the hadron equation of state soft or stiff? I conclude from Table 2 that current observational evidence, while far from conclusive, tends to favor neutron interaction models for which the calculated interaction energy becomes repulsive at subnuclear densities. For the TI model the calculated properties of neutron stars lie comfortably within the suggested "observational" range, while stars calculated with a soft hadron equation of state possess properties which are at, or near, one limit of the range obtained from an analysis of the current observations. It is to be hoped that through further analysis of existing data (such as that in progress on the 12 pointed obser-

Table 2. Observing neutron stars: properties sensitive to the hadron equation of state.

Property	Observation	Interaction model		Current status
		R	TI	
$M_{max}/M_\odot$	X-ray Doppler shift plus optical observations	1.4 ± 0.2	1.8 ± 0.2	$1.4 \leq M_{max}/M_\odot \leq 3$
R (km)	Blackbody fit to burster spectrum	9.8*	16*	Minimum radius, $R_{min} \sim 9 \pm 2$
I_c/I	No structure in Her X-1 $\Omega(T)$ noise	0.04*	0.56*	$I_c/I \gtrsim 1/2$ if $1 \lesssim \tau \lesssim 10^2$ days
Reference oblateness, ϵ_0, and critical strain angle, σ_c/μ, or minimum angular velocity at time of crust formation, Ω_0^{min} (sec^{-1})†	Stellar wobble as origin of 35-day periodicity of Her X-1	$\epsilon_0 \simeq 0.05$, $\Omega_0^{min} \simeq 4600$, or $\sigma_c/\mu \sim 0.05$	$\epsilon_0 \simeq 0.001$ $\Omega_0^{min} \simeq 320$ or $\sigma_c/\mu \sim 10^{-3}$	Origin of 35-day clock not yet determined
$I_{45} = (I/10^{45})$ g-cm^2	Crab pulsar luminosity, L_c ($10^{38} \lesssim L_c \lesssim 10^{39}$ erg/sec)	0.9*	2*	$0.2 \leq I_{45} \lesssim 2.2$
Interval, Δt (years), between starquakes due to pulsar spin-down†	Successive macroglitches in fast pulsar $P(t)$	$(\Delta t)^*_{Crab} \sim 10^2$	$(\Delta t)^*_{Crab} \sim 5$	$(\Delta t)_{Crab} \sim 5$†

*Calculated property for a 1.4 $M_\odot$ star. †See Pandharipande *et al.* (*43*) for further details.

Table 3. Observing neutron stars: other properties.

Property	Observation	Current status
Surface magnetic field, B	Spectral features in pulsed fraction of x-radiation	$4 \times 10^{12} \leq B_{Her\ X-1} \leq 6 \times 10^{12}$ gauss; $B_{A0115-63} \sim 2 \times 10^{12}$ gauss
Magnetic moment, μ	Spin-up for stars accreting from Keplerian disks	$0.1 \leq \mu_{30} \leq 10^2$ Best fit for 1.3 $M_\odot$ TI star is $\mu_{30} \sim 0.5$ gauss-cm^3
Surface temperature, T	Upper limit on flux of nonpulsed soft x-rays from radio pulsars*	$T_{Crab} \lesssim 2.5 \times 10^6$ K†; $T_{Vela} \lesssim 1.2 \times 10^6$ K‡
Hadron superfluidity	Dynamic response to pulsar glitch	$4 \leq \tau_{Crab} \leq 15$ days; $90 \lesssim \tau_{Vela} \lesssim 450$ days; $\tau_{1641-45} \sim 85$ years
	Structure in $\Omega(t)$ noise	None seen for Her X-1 or Crab pulsar

*In arriving at a maximum surface temperature, I have assumed blackbody radiation, taken $R \sim 15$ km and neglected any general relativistic corrections. †Toor and Seward (*79*). ‡Results obtained by R. Harnden and collaborators, using the Einstein Observatory, as reported by Lamb (*74*).

vations of Vela X-1 made with HEAO-1 by P. Boynton, F. K. Lamb, S. Pravdo, and K. Wood), better theoretical calculations of these and other properties, and further observations, the question may be decidable in the near future.

Future Prospects: An X-ray Timing Explorer?

It is evident from this brief account that much theoretical work remains to be done on the physics of compact x-ray sources. Thus, while quantitative models exist for the large-scale properties of the magnetosphere of accreting neutron stars and for their maximum mass and internal structure, there exist little more than qualitative pictures of the fundamental processes at extremely high temperatures in the superstrong magnetic fields found near the stellar surface, and only semiquantitative models for nuclear reactions under the extreme conditions encountered in neutron stars or for the dynamical properties of the stellar interior. Quantitative models likewise exist for the physical processes occurring near accreting black holes, or, in the case of spherical accretion, under the extreme conditions prevailing near the surfaces of accreting degenerate dwarfs, but there exist little more than qualitative pictures for the case of nonspherical flow or for degenerate dwarf magnetospheres (*4*).

Still, where there are quantitative models, it may be argued that theory is ahead of observation, in that detailed study of a comparatively small number of known compact x-ray sources of special astrophysical interest is urgently needed to test existing theory and provide a basis for an improved understanding of the physics of these remarkable objects. To cite one example, dense regular sequences of pulse phase and x-ray flux measurements for the pulsating x-ray sources are needed to test the validity of a universal torque-luminosity curve (*42*), determine the nature of torque fluctuations, and provide quantitative information on their level, thereby making possible an improved understanding of disk accretion, dynamic models of crust-core coupling, and the evolution of slow rotators. Similarly, because the discovery of a black hole is of such fundamental importance (as verification of the general theory of relativity in a different physical regime), one might hope that a sustained observational effort would be devoted to the discovery of candidates other than Cyg X-1, while detailed study of rapid time variability in Cyg X-1 and other candidate sources might make possible the characterization of physical processes in the region nearest a black hole (*20*).

Considerations of this kind led the participants at the recent Workshop on Compact Galactic X-ray Sources (*4*) to recommend that a temporal and broad-band spectroscopic mission be added to the NASA Explorer program. An X-ray Timing Explorer, with a substantial area (~ 1 m^2) of proportional counters (2 to 35 keV) collimated to $1^{\circ 2}$ and capable of extended observations over most of the sky, would greatly extend the capabilities of the two x-ray astronomical satellites that reentered the atmosphere in the spring of 1979 (SAS-3, which had flexible sustained pointing and a modest area, and HEAO-1, which had a very large area but restricted pointing capabilities). A Timing Explorer is required for the x-ray astronomical community to continue the highly successful temporal studies which have led to such rapid progress in the theory and observation of compact x-ray sources during the past decade, and would enable the astrophysical community to address directly the key scientific problems in the behavior of compact x-ray sources (*4*).

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80. This article is based on invited papers presented at a conference on X-ray and Gamma-ray Astronomy in the 1980's held at Spitzingsee, West Germany, in October 1978, under the auspices of the European Science Foundation and the National Academy of Sciences and at the Workshop on Compact Galactic X-ray Sources, held in Washington, D.C., in April 1979. I thank my colleagues at both meetings for many useful conversations, the National Science Foundation for its support, the Aspen Center for Physics for its hospitality during the writing of this article, and my colleagues D. Q. Lamb and F. K. Lamb for a critical reading of this manuscript.

Hybrid Dysgenesis in *Drosophila melanogaster*

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Drosophila geneticists have recognized the occasional occurrence of dysgenic traits such as mutation, chromosomal aberration, distorted segregation, and sterility (*1, 2*). These traits were usually found in experiments with flies newly caught in the wild. Male recombination has also been found under similar conditions (*3*), generally associated with other dysgenic traits, particularly with mutator activity (*2*). These results had been attributed to mutator genes apparently widespread in natural populations, but this interpretation led to an enigma. It was difficult to understand how such genes could be maintained in natural populations since their effects would be expected to result in a drastic reduction of population fitness (*4*).

The first contribution to clarification was that of Kidwell (*5*) who, on the basis of several crosses, suggested that high frequencies of dysgenic events do not occur under natural conditions but are the result of genetic interactions between strains newly derived from wild flies and long-established laboratory stocks. This idea was developed further, and the term "hybrid dysgenesis" has been proposed to designate a "syndrome of correlated genetic traits that is spontaneously induced in hybrids between certain mutually interacting strains, usually in one direction only" (*6, 7*).

Kidwell, Kidwell, and Sved (*8*) showed that the stocks they used fell into two categories called P and M. It soon appeared that strains established from newly caught wild flies were of the P type, whereas long-established laboratory strains were of the M type (*8-10*).

We have been investigating a specific kind of female sterility (called SF sterility) which occurs in F_1 females obtained from crosses between two types of mutually interacting strains called inducer and reactive; the reactive strains exist only in laboratories. The sterility test permits analysis of the genetic factors involved in this phenomenon. The reactive condition may be viewed as a particular cytoplasmic state of the oocytes, which is mainly maternally inherited. However, this state is ultimately controlled by a chromosomal polygenic system. The inducer condition is determined by a chromosomal factor that is probably a transposable element. Transpositions may occur with high frequency but require a reactive cytoplasm.

The inducer-reactive interaction leads, in addition, to other dysgenic traits, notably to nondisjunction and mutation (*11*). Therefore, this system appears to fall within the domain of hybrid dysgenesis. It is now established that *Drosophila melanogaster* exhibits at least two causally independent systems of interacting strains: I-R and P-M (*10*). Most, if not all, laboratory stocks or wild populations belong to one category of both systems and a dual designation is now possible for all of them (*10, 11*). A review of the I-R system may clarify the understanding of hybrid dysgenesis and may be of particular interest because (i) the data obtained on I-R interaction could stimulate and facilitate comparative studies with other similar systems already (or still to be) described, and (ii) the various impli-

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