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Journal

Contemporary Physics, 32(2)

ISSN

0010-7514

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Publication Date

1991-03-01

DOI

10.1080/00107519108213806

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Peer reviewed

Neutron stars and black holes in binary systems

VIRGINIA TRIMBLE

Neutron stars and black holes can find themselves with close stellar companions through birth or later accident (section 1). The systems give rise to intense variable X-ray sources and born again pulsars (section 2) and perhaps to still odder things (section 6). They provide the best measurements of neutron star masses and the most persuasive evidence for the existence of black holes in the real world (section 3). Most of the basic evolutionary (section 1) and radiation mechanisms (section 4) required to model the observations have been in place for a decade or more and have survived discovery of new phenomena every couple of years. Many of these involve disks of gas accreting onto the stars (section 5). These disks are perhaps prototypes for those in the cores of quasars. Some problems remain with (a) relative numbers of objects in various evolutionary phases and (b) a few extreme individual systems such as SS 433 and 1957+20 (section 6).

1. Introduction: Formation, detectability, and fate of binaries with neutron star and black hole components

One percent or so of all stars start life massive enough that, evolving in splendid isolation, they would leave neutron star or black hole remnants (rather than a white dwarf). The white dwarf (WD)/neutron star (NS) dividing line falls in the range 5–9 times the mass of our sun, and the lower limit to make a black hole is even less well known, but probably at least 50 solar masses. One solar mass ($M_{\odot}$) is 2×10^{33} g, the astronomical community being the last refuge of unregenerate cgs-ers. The boundary lines are much higher than the $1.4 M_{\odot}$ maximum mass that can be supported by degenerate pressure (Chandrasekhar limit). This happens because stars shed all their lives, and more toward the end (like aging poodles).

At least half the dots of light in the sky are really pairs of stars, with the stars close enough together to affect each others' evolution. The more massive star at the beginning we will call the primary component of the system forever after, no matter what happens to the masses later. The presence of the secondary distorts the shapes of the gravitational equipotential surfaces around

the primary (Roche geometry) and so encourages both transfer of material to itself from the primary and loss of gas from the system as a whole (figure 1). This means that the dividing line to produce compact remnants referred to above rises to $10\text{--}15 M_{\odot}$; but it also means that the eventual death of the primary in a supernova explosion does not normally unbind the system [1].

Thus a third or so of the neutron stars and black holes that form will do so in close binaries. This supply can be augmented, first, through collapse of a white dwarf in an existing binary system to a neutron star when accreted material drives it above the Chandrasekhar limit [2], and, second, through incorporation of a previously existing neutron star into a binary system by tidal capture when stars are crowded close together in a cluster [3]. The signature of the first process should be a young neutron star (high magnetic field) in an old system (orbit circularized and perhaps with rotation and orbit periods synchronized by tidal forces) and that of the second process should be an old neutron star (low magnetic field) in a younger system (eccentric or unsynchronized orbit; short life expectancy). Because neutron stars can both gain and lose angular momentum over their lives, rotation period is not a good age indicator [4], though the ratio of period to its first derivative ('slowing down time') can be.

Binary neutron stars or black holes are detectable and recognizable as such under two circumstances. First, the neutron star can act as a pulsar, radiating away its rotational kinetic energy as magnetic dipole radiation at

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Figure 1. Equipotential surfaces in the rotating coordinate system of a binary with initial masses in the ratio 2:3. The larger Roche lobe surrounds the more massive (and larger) star, the two lobes meeting at point L_1 . A star which expands to fill its lobe can drizzle material onto its companion with high efficiency. There also exist contact systems in which both stars fill their lobes (orbit periods generally less than one day) and common envelop systems in which (usually as a result of rapid mass transfer) material extends out as far as L_2 and can be lost from the system, carrying energy and angular momentum with it. If the stars are assumed to be main sequence stars of $3M_\odot$ and $2M_\odot$ with the radii to scale as shown, then the orbit period would be about six days.

the rotation frequency (leading in turn to acceleration of electrons that radiate at radio to X-ray wavelengths). This will happen if (a) the neutron star has $B^2/P^4 \gtrsim 10^{21} \text{ G}^2 \text{ s}^{-4}$ where B is surface dipole field in gauss and P is rotation period in seconds and (b) the surroundings are close enough to a vacuum that the MHz radiation characteristics of a pulsar is not below the local plasma frequency. The first condition is met when neutron stars are first born or when they have been spun back up to short periods by accreted gas (bearing angular momentum). The second condition requires that they be isolated or in orbit with a windless companion (white dwarf, neutron star, or black hole). Systems with WD and NS secondaries are known, but none with black holes so far.

Second, both neutron stars and black holes are deep gravitational potential wells. Gas flowing down into these must radiate away nearly $10^{20} \text{ erg g}^{-1}$. Gas inflow rates between 10^{-13} and $10^{-7} M_\odot \text{ yr}^{-1}$ will result in X-ray emission detectable from a source almost anywhere in the galaxy, given current survey sensitivities. At lower gas accretion rates, the X-ray luminosity falls below $10^{32} \text{ erg s}^{-1}$. At higher ones, the accretion luminosity is so large that radiation pressure on

inflowing gas exceeds the force of gravity, and X-rays are likely to be downgraded to ultraviolet and visible photons working their way out through the piled-up gas. The luminosity, or L/M ratio, at which the two forces are equal is called the Eddington limit.

Accretion at the right rate can occur from the wind of a massive or evolved secondary. (Stars shed.) It can also occur through the distortion of gravitational potentials. This is called Roche lobe overflow and normally dumps gas into a disk around the primary (see figure 2) from which it gradually works its way in. In general, wind accretion dominates for secondaries of more than $\sim 8 M_\odot$ and Roche lobe overflow for secondaries below $1.5 M_\odot$. Only one or two known systems fall in between. When the secondary completes its evolution, these two classes should give rise to binary millisecond pulsars with neutron star and white dwarf secondaries, respectively. Later angular momentum loss can bring the stars back into contact, producing a second X-ray phase, at least for white dwarf secondaries [5].

Binary neutron stars or black holes which are neither pulsars nor accretion X-ray sources are unlikely to be recognized as such. Their orbits naturally cause doppler shifts in the spectral lines of their secondaries, but the shifts will look just like ones due to a normal, faint, companion star of the same mass.

How do these systems end up? The possibilities that come to mind are that the pair can unbind or merge; or one star may destroy the other; or (for wide enough pairs), two neutron stars or black holes may orbit each other silently for times longer than the present age of the universe. Detailed evolutionary calculations indicate that each outcome occurs at least occasionally. If the second star also evolves to the sort of supernova that leaves a neutron star behind, the explosion will sometimes, but not always, unbind the system. Thus an old and a young neutron star will either fly off in opposite directions or continue to orbit.

Mergers come about when angular momentum is drained from the system. A magnetic wind from the normal star will do this rather efficiently. Gravitational radiation sets a lower limit to the rate of angular momentum drainage, and pairs with orbit periods less than about half a day are guaranteed to merge in less than 10^{10} yr . Mergers of two black holes lead to nothing but a burst of gravitational radiation. But two neutron stars or neutron star plus black hole could be quite spectacular, if the available $\gtrsim 10^{53} \text{ ergs}$ is radiated at all efficiently. Connections with the production of neutron-rich isotopes of heavy elements [6] and with gamma ray bursts [7: sect. 6.G] have been suggested.

Finally, the companion can melt away from a combination of winds, Roche lobe overflow, and evaporation due to heating by incident X-rays or pulsar

Figure 2. Idealization of a highly-evolved binary, in which an extended secondary is transferring material through L_1 back onto a compact primary (white dwarf, neutron star, black hole). Diagram is drawn for a mass ratio compact: normal of about 1.5. Transferred gas has too much angular momentum to settle directly onto the compact object and so forms an accretion disk, with a hot spot where the gas stream hits the disk. Gradual outward transport of angular momentum in the disk (presumably by magnetic fields and turbulence) allows accretion onto the star, liberation of gravitational potential energy, and radiation of that energy.

radiation, leaving a single neutron star with a mix of apparent young and old characteristics.

A curious gap in the current literature is the absence of a reasonably complete catalogue of X-ray binaries and related objects to update that of Bradt and McClintock [8]. Nagase [9] tabulates 30 massive X-ray binaries and van Oijen [10] a slightly smaller number with optical identifications; Parmar and White [11] list 25 low mass systems (LMXBs) with well-established orbits; and Rappaport *et al.* [12] tabulated properties of 14 binary and millisecond pulsars (but as many again have appeared in IAU Circulars since then). More extensive references on binaries with neutron star and black hole components and reviews of many other topics in binary star astronomy will be found in reference [13].

2. Types of systems

Table 1 summarizes major categories and some of the deviant objects that are known or have been suspected to consist of neutron stars or black holes in binaries. Numbers are those known through late 1990. The X-ray binary inventory of the Milky Way is complete for systems with steady luminosities above about 10^{34} erg s $^{-1}$. It is, however, incomplete for the transient emitters with Be star companions; Be stars display emission lines from gaseous shells, have masses of 3–12 $M_{\odot}$ and surface temperatures of 15–20 000 K, and are still fusing hydrogen to helium as their primary energy source. The name comes about because *B* indicates a surface temperature near 20 000 K, and *e* refers to the emission lines. The pulsar inventories are incomplete for (a) short rotation periods, (b) short orbit periods, (c) low luminosities, and (d) distances of more than a couple of hundred parsecs (1 pc = 3×10^{18} cm).

2.1. A few words about names

This section can be profitably skipped by anyone who does not expect to have to read research papers in the field and is willing to trust that the strange melange of designations in later sections can, in principle, be sorted out.

The brightest few X-ray sources, found in early rocket flights, ended up with names such as Cygnus X-1, X-2, X-3 etc. (the Magellanic Clouds being regarded as constellations for this purpose). Some of these are better known by the names of the corresponding optical object, such as HZ Her (a variable star designation), γ Cas, and X Per.

The commonest sort of label consists of four digits indicating right ascension in hours and minutes, followed by a + or – sign and two digits for the declination in degrees. Rounding can be either uniformly downward or to the nearest whole number, so that 1915-05 and 1916-05 are the same source (and in the same paper at that). Two sources that would otherwise have the same name can be distinguished with tenths of a degree (2030 + 375 or 2030 + 37.5) or as A,B,C, e.g. 0021-72A and 0021-72B, two millisecond pulsars in the globular cluster 47 Tucanae.

A dozen or so sources are better known by their galactic (longitude and latitude) coordinates in degrees, as GX 1 + 4, GX 304 – 1, etc. These are readily distinguished by having one, two or three digits before the sign, while the equatorial coordinate versions always have four, even if the first is a zero.

Some letters in front of the numbers provide further information about the objects. X is an X-ray source, B a burster, P a pulsator, and T a transient. XPT 0332 + 53 is thus a pulsating, transient X-ray source. Other letters

Table 1. Classification of binary star systems with neutron star or black hole components and related objects

Type	Numbers known	Strength of evidence	Rotation periods	Orbit periods	Constituents	Prototype or example
Binary pulsar	21	good	1.6–1066 ms	0.075–358 day	NS + NS or WD	Psr 1913 + 16
Globular cluster pulsars	26	half binaries	3–290 ms	0.075–191 day	NS + WD	Psr 2127 + 12ABCDE (in M15)
Single milliseconds pulsars	20	—	1.6–100 ms	—	NS	Psr 1937 + 21
Massive X-ray binaries	30	good	0.7–850 s	16–188 day	NS + supergiant	Vela X-1
Be star X-ray binaries	≥ 70	good	0.06–835 s	1.4–41 day	NS + hot star	GX 304-1
Black hole candidates	4–6	good	none	0.3–5 day	BH + star	Cyg X-1
SS 433	1	good	?	13.1 day	BH or NS + normal star	SS 433
Low mass X-ray binaries	100					
with optical data	36	good	0.13–122 s	0.008–12.5 day	NS + MS/RG/WD	Sco X-1
in globular clusters	12	fair	ms?	11 min–8.5 h	NS + MS/RG/WD	4U 2127 + 12 = AC211 (in M15)
in galactic bulge	50	fair	ms?	hours–days	NS + MS/RG/WD	GX 17 + 2
Quasi-periodic oscillation sources	10	good	ms?	0.008–10 day	LMXRB subset	Cyg X-2
Gamma bursters	100s	nil	?	—	NS? + ?	1979 March 5
XRb in supernova remnant	≤ 1	nil	6.98 s	—	NS? merged WD pair?	1E2259 + 586 = CTB 108
Geminga	1	nil	60 s?	—	NS + ?	Geminga

indicate the satellite in whose catalogue the source appears: A = Ariel, U = Uhuru, H = HEAO-1, G = Ginga, E = Einstein (and possibly sometimes Exosat), S = SAS, M = OAO. Further refinement is possible; 4U is the fourth Uhuru catalogue, for instance.

Mercifully, the binary and millisecond pulsars have been discovered late enough and faint enough to be called PSR 1913 + 16 etc. from the beginning, though the ambiguity in direction of roundoff remains. Ones in globular clusters also get called M15A, M15B, etc.

A few classes of objects are common enough and well enough defined to tempt researchers to acronymy. Commonest is LMXRB or LMXB for low mass X-ray binaries (companions $\lesssim 1.5 M_{\odot}$). The logical opposite, HMXRB (high mass XRB) occurs occasionally [14], but MXRB (massive XRB) is commoner and MXB not unknown, but unfortunate, owing to the possible confusion with a hypothetical burster in the OAO catalogue. Massive systems (companions $\gtrsim 8 M_{\odot}$) rarely burst, but only the true aficionado knows enough of the six digit numbers by heart to sort out what is meant in every possible case.

The present paper attempts no rationalization of the system. Where a specific reference is cited, the name is usually the one used there. Otherwise it is a random choice from the menu.

2.2. Massive X-ray binaries

These systems are the ones we most obviously expect—a neutron star left from the death of a massive ($\geq 10 M_{\odot}$) primary in orbit with its secondary, which is also fairly massive, if only because of transfer of material from the evolving primary in the past [15], though some gas is also lost to the system [16]. The subspecies are optically identified with two slightly different kinds of secondary stars. Some are highly evolved stars with strong intrinsic winds and life expectancies not much more than 10^4 yr in their current condition. Others are less bright, less massive, and less evolved, but that they are shedding is revealed by emission lines radiated by hot, tenuous gas. These have life expectancies nearer 10^5 yr.

Common sorts of variability and periodicities include (a) pulsation of the X-rays at the neutron star rotation period (because accretion occurs preferentially along the tilted magnetic axis [17], (b) eclipse of the X-rays and doppler shifts of the pulsation period and of the secondary star's spectral lines at the orbit period, (c) rapid erratic flaring from lumps in the accreting gas, (d) secular evolution over 10^4 – 10^5 yr, (e) mild cyclic variations with 0.1–2 yr periods, perhaps attributable to precession, (f) recurrent transient flares at the orbit period in non-circularized systems [18,19] or at an instability

period of the donor star [20–22] associated with sudden increases in mass transfer rate, and (g) spin-ups and downs of the rotation period; up when the sources and bright and rapid accretion is bringing in more angular momentum than magnetic dipole radiation is carrying away [14,23] and down the rest of the time, but the real situation is a good deal more complicated [24–27].

What do we learn from all this? First, the neutron stars have magnetic fields of 10^{12} G or more, like pulsars [28,29]. Second, the neutron star birth events have given the systems something of a velocity kick, also like pulsars [30]. Third, for those systems where we see doppler shifts for both components, the implied primary mass makes sense for a neutron star [31].

Fourth, the minimum primary mass needed to produce a black hole in a close binary is at least $40 M_{\odot}$ [32], based on the present mass of the secondary in 4U 1223-62 (the corresponding limit for single stars is unknown). And fifth, the birthrate of these systems must be about as large as that of single (pulsar) neutron stars to account for the ones we see, given their short lives. The pulsar birthrate is about one per sixty years [33]. Keeping up the supply of the very massive XRBs takes only about one new one per millenium [15]. This number is fairly firm because our inventory of these systems is growing at only one or two per year [34]. But the known Be star systems are all rather close to us [10] and new ones keep popping up by the handful [35,36], so that the estimated birthrate of one per century is really a lower limit.

2.3. The black hole candidates

For our purposes, the essential property of a black hole is an effective size close to the Schwarzschild radius, $R = 2GM/c^2$ and correspondingly deep gravitational potential well. Details of space-time geometry (especially inside) and the existence of a central singularity do not matter. The X-rays themselves constitute the evidence for some kind of compact star and are radiated by gas (typically in a disk) as it flows down in, not by the black hole itself. Thus the main distinction between a neutron star and a black hole in a close binary is one of mass with supporting evidence from the absence of any regular variability that might be attributable to rotation of a neutron star.

The maximum stable mass of a neutron star depends on the equation of state of dense matter above the range readily probed in laboratory experiments. The limit could be as low as $1.6 M_{\odot}$ [37], but a value of $3 M_{\odot}$ is generally assumed for the purpose of selecting black hole candidates. If bound baryonic configurations of $10 M_{\odot}$ or more are possible [38], then the case for the existence of astrophysical black holes in binary systems essentially disappears.

The first candidate, Cyg X-1 = HDE 226868, has survived numerous challenges since 1972, and all recent analyses based on radial velocities, light curves, and polarization concur on a mass for the X-ray component between 5 and $10 M_{\odot}$ [39–41]. The X-ray behaviour is consistent with radiation mechanisms not very different from those appropriate to neutron star systems [42–44], so it is perhaps not surprising that efforts to pick out other black holes from X-ray data alone have yielded mostly false alarms, including Cir X-1 (which later displayed X-ray bursts due to nuclear burning on a neutron star surface, [14]), 0332 + 53 (where a 4.4 s rotation period turned up [45], and GX 339-4 (with a transient optical period of 190 s [46]. X-ray signatures might include chaotic variability, with or without a low-dimensional attractor [47,48] and a complex, variable, soft spectrum [14,49].

The other two persuasive cases, LMC X-3 [50,51] and the soft X-ray transient A 0620-00 [52,53] also rely heavily on optical data. The same is true for LMC X-1, for which a plausible case can be made [14]. All have massive secondaries except A0620-00, which seems to be a cool evolved star of about $0.7 M_{\odot}$, but which must have passed through a massive XRB phase [54]. Other systems currently in the candidate pool include the soft X-ray transients GX2000 + 25 [55] and GS1354-64 [44], the LMXRB Cal 87 in the Large Magellanic Cloud [56], and an X-ray nova in Vulpecula [57].

It is worth noting that the black hole, at least in Cyg X-1, must have formed as such directly from core collapse of the primary. To drive a neutron star past stability and ‘grow’ it up to the present mass would require accretion, even at the largest possible Eddington rate, for longer than the total lifetime of the secondary.

2.4. Low mass X-ray binaries (LMXBs)

The present state of these systems is fairly straightforward. Gas flows onto the neutron star from an accretion disk which, in turn, is fed by Roche lobe overflow of a low mass secondary. Most of the systems are in the older parts of the galaxy—globular clusters, nuclear bulge, and thick disk—reflecting the multi-billion year life expectancies of the secondaries. About 35 measured orbit periods [11,58] range from 11 min to 12.5 days, corresponding to white dwarf secondaries at the shortest periods (e.g. MXB 1826-30 in the globular cluster NGC 6624), main sequence (hydrogen burning) stars in the middle, and red giants at the longest periods (e.g., Cyg X-2, GX 1 + 4). The periods are measured variously from optical doppler shifts; optical light curves of secondaries with lopsided shapes and heating; and partial occultations and

scatterings of the X-ray by the accretion disks, their winds and coronae.

The absence of total X-ray eclipses is normally advertized as an orientation effect [59], though doubt has recently been cast on this at least for one source that brightened above $10^{38} \text{ erg s}^{-1}$, most surprising if the X-rays we see are merely the fraction scattered into the line of sight [60].

Her X-1 sits between the LMXRBs and the massive systems, having a slightly evolved $2 M_{\odot}$ secondary. In addition to a 1.24 s rotation period for the neutron star and a 1.7 day orbit period, it is complicated by a 35 day brightness modulation, variously attributed to precession of the accretion disk [61,62] or to precession of the neutron star itself [63]. The strong magnetic field implied by rotationally-modulated accretion is confirmed by the presence of cyclotron resonance features [64].

Rotation periods of the neutron stars produce detectable variability only in the three slightly weird sources Her X-1 (1.24 s), GX 4 + 1 (122 s), and X1626-67 (7.7 s [65], and some fairly tight limits have been set for others [66,67]. Efforts to blame general relativistic effects for the non-detections have failed [68], leaving weak magnetic fields as the most likely alternative. The 'beat frequency' interpretation of quasi-periodic oscillations (section 6.1) says indirectly that most of the periods are ≤ 0.1 s, as a result of angular momentum added by accretion from the disks.

The accretion disks are conspicuous and dominate the optical light for all but a few systems with giant secondaries. The disks in Sco X-1 [69] and Cyg X-3 [70] apparently orient radio jets on several scales [71], while disk instabilities in half a dozen other sources are perhaps responsible for outbursts on 0.5–2 yr time scales [18].

Just how the disks are fed is less obvious than their existence. Because the secondary is usually the less massive star, its Roche lobe expands as material is transferred. This is confirmed by the increasing orbit periods of X1822-371 and Cyg X-3 [72]. Contact must be maintained by some combination of the following: (a) radiation-driven expansion of the secondary ([73] on Cen X-4; [74] on Cyg X-3), (b) gradual expansion of those secondaries near or past the end of core hydrogen burning, and (c) removal of angular momentum by magnetized winds (for main sequence and giant secondaries) or gravitational radiation (the only alternative left for systems with white dwarf secondaries).

The origin of the LMXRBs also remains something of a puzzle. Exchange and loss of mass and angular momentum in initially wide (but interacting) binaries will make some [75], but probably not as many as we see, especially in the globular clusters (section 2.5). Thus arises the need for the auxiliary mechanisms mentioned in section 1 and below.

2.5. The X-ray binaries in globular clusters

The globular star clusters in the halo of our galaxy harbour far more than their fair share of the low mass X-ray binaries—about 10%, though they account for only 10^{-4} of the galactic stellar luminosity and mass. And the clusters are not otherwise overstocked with binaries [76]. The systems in them do not differ from the field LMXRBs, though the crowding of stars in the clusters precludes optical identification for all except the giant secondary system AC211 in M15 [77] and perhaps one or two others [78–80].

In 1975, Clark [81] and Fabian *et al.* [82] first proposed that these crowded conditions were directly responsible for the large number of LMXRBs. Tidal interactions could bind a single neutron star, left from when the cluster was 10^7 yr old, to a low mass star now 10^{10} yr old. If the sources persist for 10^9 yr or more, then only about 100 primordial neutron stars per cluster are needed to get enough capture systems. This is not so many that their supernova birth events would have damaged the clusters [83], though the known sources are not quite so heavily concentrated in the densest clusters as one might have expected from capture formation [84]. The general concept remains popular [85], and tidal capture seems to be the only way to account for a few particular systems, though the capture cross sections are probably not so large as originally estimated [86]. This presents a statistical difficulty that becomes far more acute in connection with binary and millisecond pulsars in globular clusters (next section).

The best-studied alternative to tidal capture is accretion-induced collapse, in which a neutron star is created from a white dwarf that has greedily swallowed material from a companion until it passes the Chandrasekhar limit [87,88]. The problem here is that the desired collapse can arise from, at most, a rather narrow set of initial conditions [32,89,90]. This has prompted discussions of more complex scenarios involving triple systems, for which there is some observational evidence [91,92] arising from captures [93] or star exchanges between primordial binaries and primordial neutron stars [94]. These triple processes are clearly possible only in the dense environments provided by cluster cores.

The plethora of globular clusters LMXRBs and the possibility of formation mechanisms that work only there have led to proposals that the field sources originated in clusters and were either kicked out by additional encounters or liberated when clusters were torn apart by the tidal forces of the Milky Way [93].

2.6. Binary and millisecond pulsars

'The' binary pulsar (1913 + 16) and 'the' millisecond pulsar (1937 + 11), both with small rates of period

increase, implying magnetic fields of 10^{8-10} G, remained unique for several years after their discoveries [95,96]. Ordinary single pulsars radiate away their rotational kinetic energies in 10^{6-7} yr without losing much of their magnetic field. Thus these two then unique objects were quickly attributed to spinning-up by accretion during a preceding X-ray binary phase. The single millisecond pulsar was presumed to have been spun up and then liberated [97], thereby linking the two classes. This scenario is responsible for the names 'recycled' and 'born-again' pulsars.

Development of techniques for de-dispersing short pulse periods in distant, accelerated objects has led to rapidly growing inventories. The numbers in table 1 are likely to be wrong by 10–100% by the time you read them. Most of the known members of the binary and millisecond classes are faint, even as pulsars go, and about 10% of a volume-limited sample would be short period, weak field objects [98]. Three systems have companions massive enough to be neutron stars, which indicates descent from massive XRBs. The others orbit white dwarfs or nothing and could descend from LMXRBs. About three of the binary systems need not have been recycled, since the neutron stars have fields close to 10^{12} G and periods near 1 s, typical of first-time-around pulsars at 10^{6-7} yr.

The binary and millisecond pulsars are, like the LMXRBs, over-represented in globular clusters, even when you allow for searches that have focussed there. Formation scenarios are sorely taxed by the numbers. If all have come from LMXRBs, then the X-ray emitting lifetime must be shorter than the pulsar phase [99,100]. Capture and accretion-induced collapse can alleviate the situation only if they occur after or very shortly before the secondary-to-be ceases to be capable of mass transfer (otherwise the system will pass through an XRB phase anyhow). Capture formation also implies rather more primordial neutron stars than expected.

Even if capture and accretion could make enough systems, the population properties would not make sense. Both processes should produce mostly close (short-period) systems. Admittedly these are the hardest to detect. But careful consideration of the search phase space [101] says that wide systems and single millisecond pulsars are far commoner than the models predict.

Perhaps the answer is that capture normally disrupts the non-compact star, leading directly to a single millisecond pulsar [102]. In any case, the general issues of expected numbers of binary and millisecond pulsars and of where they fit into possible evolutionary schemes clearly need to be rethought. At least one known system, 0021-72A (in the direction of the globular cluster 47 Tuc, but probably a foreground object, [18] will resume existence as a LMXRB in about 10^8 yr when its current

half hour orbit has shrunk a bit further [62].

3. Properties of black holes and neutron stars derived from binaries and implications for other astronomical issues

Existence, according to the philosophers, is not a predicate. But that black holes (in the sense of objects collapsed down to or beyond their Schwarzschild radii) exist in the real world must surely count as an interesting datum. The X-ray binaries with primaries above the maximum possible for neutron stars (section 2.3) currently provide the most persuasive evidence for such black holes. The difference between Kerr (rotating) and Schwarzschild (non-rotating) geometry should affect the spectrum and light curve of Cyg X-1 in a predictable manner [103] and may eventually tell us what sorts of black holes are out there. The other major class of candidates are galactic centres with quasar like activity [104,105] or with very compact cores, [106] for which the link between observations and black hole existence is rather less direct.

Neutron star properties that might be illuminated by the light of binary systems include masses, sizes (hence the equation of state of dense nuclear matter), and evolution of magnetic field strength. The best mass values come from the first binary pulsar, 1913 + 16, whose highly eccentric, 8 h orbit mimics that of Mercury in undergoing a general relativistic perihelion advance, but measured in degrees per year rather than in seconds per century. The relativistic effects permit sorting out of the orbit inclination angle and component masses as 1.44 and $1.39 M_{\odot}$ [107]. These are quite close to the expected masses at formation (e.g. what is needed to account for the neutrino burst from supernova 1987A), and they rule out only the very softest equations of state [108].

Additional insights from this system include [107, 109–111] (a) decay of the orbit at a rate that confirms the quadrupole formula for emission of gravitational radiation by a pair of point masses, (b) changes in the pulse and interpulse profiles indicative of geodetic precess at the expected rate, (c) stability of the pulse period at a level requiring the constant of gravity, G , not to change faster than $\dot{G}/G = 1.2 \pm 1.3 \times 10^{-11} \text{ yr}^{-1}$ and the energy density in gravitational radiation with frequencies between 10^{-12} and 10^{-9} Hz not to be larger than 4% of that needed to close the universe. A binary pulsar in the globular cluster M15 with a similar, 8 h eccentric orbit should begin to reveal its component masses in a few years [112]. That the second star is also a neutron star in this system already seems virtually certain.

Masses of the neutron stars in X-ray binaries have much larger error bars. Data exist only for massive

systems and are not inconsistent with them all falling close to $1.5 M_{\odot}$ [108], but also not inconsistent with some being closer to $2 M_{\odot}$. The absence of rotationally modulated X-ray emission in the LMXRBs to use as a doppler clock means that we have not even approximate masses for their neutron stars, which should have accreted several tenths or more of a solar mass over their lifetimes.

Two kinds of observations have something to say about neutron star radii and equations of state. First, the shortest known rotation periods of 1.6 ms require only moderately compact stars and rule out only very stiff equations of state [108]. A 0.5 ms pulsar, as briefly advertized in SN 1987A would, on the other hand, have been severely restrictive, probably requiring cores of pions or strange quark matter rather than traditional neutron stars [113].

Second, X-ray bursts ought to provide information on sizes. But they are rather a disappointment. Pion and strange quark stars can experience much the same sorts of bursts (section 4.3) as conventional neutron stars [114]. Nor does it turn out to be possible to extract masses and radii either from the gravitational redshifts of spectral features or from the peak luminosities interpreted as Eddington limits for objects radiating at the X-ray spectral temperatures. The 4.1 keV spectral feature comes at so nearly the same energy in all sources where it is seen that blaming it on a gravitationally redshifted iron line would mean that the neutron stars all had implausibly similar masses and radii [115,116].

Equally sadly, the burst X-ray continua are not really black bodies, and the conversion from colour temperature to effective temperature is extremely uncertain [117–119]. This also spoils the attempt to use X-ray burst fluxes and the Eddington limit to establish an independent size scale for the Milky Way galaxy. Ignoring all possible problems leads to the interestingly small value of 6 kpc for our distance from the centre [120].

The implications of binary data for the evolution of neutron star magnetic fields is currently in even greater disarray. The usual view of single pulsars is that they begin life with fields 10^{12} G (not necessarily instantly [121]), which decay exponentially with e-folding times a bit less than 10^7 yr. The time scale comes from measured pulsar periods, period changes, and kinematics [122] and can be explained, for instance, by ohmic heating [123].

This cannot be the whole story. Fields of 10^{8-10} G have managed to persist in some LMXRBs beyond 10^8 yr [124,125] and in all of the binary pulsars, though the secondaries and orbits say that some of these must be 10^9 yr old.

Perhaps, then, field decay bottoms out at some finite value [126,127]. This takes care of the binaries (provided

you—and the stars—are a bit flexible about the precise value and how long it takes to get there). But there is still a problem. If the keV features in the spectra of gamma ray bursters (section 6.7) are cyclotron resonances in fields of 10^{12-13} G near the surfaces of neutron stars (and there do not seem to be any very promising competitors [128,129]), then the large number of bursters within a few hundred parsecs of us means that even rather old, presumably single, neutron stars are still highly magnetic.

Romani [130] Shibasaki *et al.* [131] and others have proposed reconciling this apparent contradiction via accretion-induced field decay. Single neutron stars never drop much below 10^{12} G, while binary ones are further eroded during the accretion X-ray phase. Large amounts of accreted material lead to the smallest residual fields when accretion stops and we see the recycled pulsar. The jury is still out on this one.

4. Radiation processes

The primary energy sources in X-ray binaries and recycled pulsars are accretion and rotation, respectively. The radiation we actually detect has, however, undergone a good deal of reprocessing since its liberation as kinetic energy of infalling gas or as magnetic dipole radiation at Hz–kHz frequencies. The X-ray bursters appear to represent the sudden liberation of nuclear energy and are the only context where this normally-dominant source is important for neutron stars and black holes in binaries.

4.1. Recycled pulsars

The mechanism by which pulsars convert between 10^{-7} and 0.1 of their available power to low frequency, polarized radio radiation was mysterious when they were discovered in 1967 and remains so [132]. There is something approaching a standard model [133,134], involving electron–positron pair production and acceleration in a magnetosphere and radiation by coherent particle bunches as they move along curved field lines [135,136], and I do not pretend to understand it. This model is not, however, so well established as to preclude an average year from seeing the launch of a couple of alternatives [137,138]. The binary and millisecond pulsars do not, so far, seem to have contributed anything to the debate.

4.2. X-ray binaries

Virtually all well-studied sources display spectra more complex than a single power law or black body curve; many have emission or absorption features; and nearly all vary on most of the time scales (rotation, orbit, flicker,

flare, burst, transient...) on which total luminosity varies. It is often, though not always, possible to describe a particular source in terms of a couple of components that act more or less independently (for instance, radiation from the accretion disk plus radiation from the boundary layer between it and the neutron star). Additional complications come from non-thermal processes in the strong magnetic fields of the younger systems and from coronae around the disks in the older ones. While the picture is untidy, there do not seem to be any fundamental problems, which is perhaps why no comprehensive review of the subject seems to have been published. The following paragraphs address processes thought to be important in largish numbers of systems.

The cyclotron energy, $h\nu_B$, is $12(B/10^{12} \text{ G}) \text{ keV}$ and so falls in the X-ray region for the fields of young neutron stars. Features between 20 and 60 keV in the spectrum of Her X-1 were the first to be understood in terms of cyclotron resonances [139]. GX 1 + 4 and 4U0115 + 63 similarly reveal fields of $2\text{--}5 \times 10^{12} \text{ G}$. More generally, a large portion of the continuous spectra of massive XRBs can be reproduced by cyclotron emission from a range of fields around the star and subsequent scattering by hot electrons [140]. The standard calculation of Eddington luminosity assumes that radiation pressure arises from Thompson scattering by electrons as the only opacity. The effect of cyclotron absorption is, therefore, to lower the maximum possible accretion luminosity of X-ray binaries [141].

The K line of iron at 6.4–7.1 keV (depending on how many electrons the atom has) is the strongest discrete emission feature seen in X-ray binaries, occurring both in high mass systems like LMC X-4 and in many low mass ones [142,143]. The emitting gas can be a relatively tenuous corona around the accretion disk [144] or relatively dense condensations in circumstellar material [145].

Emission lines from other elements should arise in the same gas, and K lines of ionized nitrogen and oxygen are seen in spectra of the few sources bright enough to have been studied [146]. Because the lines are closely spaced in energy and weaker than the iron one, larger X-ray collecting areas and higher spectral resolution than have so far been available will be needed before they can be used as plasma diagnostics.

The continuous spectra of X-ray binaries must begin as roughly a black body at the neutron star surface (or inner edge of the accretion disk for black hole systems). Some of this component reaches us from some sources [145,147]. Additional approximately black body emission arises from the boundary layer between neutron star and disk [148] and from the disk itself [149]. But the photons that actually reach us have been heavily reprocessed. A detailed calculation of radiative transfer

in an accreting, magnetized gas column stretches the limits of available computational techniques [150]. But the net effect is rather well described as Comptonization. That is, the average photon is Compton scattered once or twice on the way out, so that the emergent spectrum roughly reflects the velocity distribution of the scattering electrons, without being completely thermalized at the effective temperature of the scatterers. These can be located in the accretion flow [151], in the boundary layer [152], in the disk coronae or elsewhere in the system [145,148,149]. In systems with optically thick disks, oriented edge-on to us, X-rays scattered in the disk corona can be the only ones we see [153].

4.3. X-ray burst sources

These bursters are (in extreme contrast to the gamma ray ones of section 6.7) one of the minor triumphs of theoretical astrophysics, having been successfully modelled very soon after their discovery [154] as explosive nuclear burning [155]. The bursters are a (large) subset of the low mass X-ray binaries that brighten up to near the Eddington luminosity in seconds or less and fade back in $\lesssim 1 \text{ s}$ to minutes. They repeat, some more or less regularly, over hours to days. Bursting occurs preferentially in the fainter LMXRBs and in ones of relatively high metallicity [156]. Peak spectrum is roughly a black body which cools as the burst fades. Averaged over time, the burst luminosity is only about 1% of the steady X-ray flux. In the sources with optical identifications, the bursts can also be followed in visible light [157]. Lewin and Joss [84] provide an excellent summary of the work up to that time and of the evidence that the sources are indeed LMXRBs.

The 'best buy' model for the phenomenon is closely related to the nova mechanism. Hydrogen gas accreted by a neutron star, like that accreted by a white dwarf, eventually is processed to helium. On a white dwarf, hydrogen burns steadily at some accretion rates, but accumulates and explodes episodically at others. On a neutron star, hydrogen burning is always peaceful, but helium burning is sporadic and explosive for a wide range of conditions [84]. These thermonuclear explosions heat the surface of the star more or less uniformly, so as to produce roughly black body emission which cools and fades as the fuel is used up, in agreement with the observations.

Within the framework of this model, one weakness remains—the bursts sometimes happen closer together than the time over which accretion could possibly provide enough fuel for the second burst. X1608-52, for instance, had two comparably strong bursts only ten minutes apart [158]. Attempts to understand this have proceeded along the lines of burning hydrogen in some

but not all bursts or of hoarding unburned helium between bursts [159,160].

A single object, the rapid burster MXB 1730-335, sometimes also bursts at closer intervals of seconds to minutes and does not cool as it fades. Its behavior is fairly confidently attributed to instabilities in accretion rate [84,161].

5. Accretion disks

Accretion disks (see figure 2) first received serious astrophysical attention in discussions of the formation of the solar system in the early twentieth century. The most unambiguous evidence for them comes from the cataclysmic variables, where their sizes are measured by the duration of the eclipses they cause and their velocity structures are probed by the profiles of the lines they emit [162]. They are also invoked to explain behaviour of quasars and some X-ray binaries. The first models for the three applications are roughly contemporaneous (for QSOs [163], for CVs [164], for XRBs [165]).

Much of the enthusiasm for studying the XRB disks derives from the hope that they will be dominated by the same physical processes as the quasar ones and so help us to understand the larger (in centimeters if not in intellectual challenge) problem. So far, the first half of the hope seems to be fulfilled, the latter half not obviously so. The notation used to describe energy and momentum transport in the disks comes from Shakura and Sunyaev [166], who collected many of the uncertainties into a single viscosity parameter. Pringle [167] and Petterson [168] have reviewed disk structure and stability; and there has been a whole conference devoted to the subject [169]. Early important papers are reprinted with commentary by Treves *et al.* [170].

Disks must exist, at least in low mass X-ray binaries, because gas coming from Roche lobe overflow will have too much angular momentum to fall directly onto the neutron star. Observational, as opposed to logical, evidence for the disks comes from spin-up of neutron star rotation periods, variable optical emission from the X-ray illuminated disk gas, and periodic dips in X-ray intensity (varying in depth with wavelength and time and lasting as much as 1/3 of the orbit period) indicative of opaque gas well away from the accreting star.

To model such a star, one writes down differential equations (roughly equivalent to the equations of stellar structure) to describe the conservation of mass, energy, and momentum (in three dimensions), the equation of state, the cooling (radiation) processes, and the energy release rate. Boundary conditions must be imposed at the outer edge of the disk where the incoming gas stream strikes it and at the inner edge, where the disk encounters the surface of the neutron star, a magnetosphere, or the

last stable orbit around a black hole. Self-gravitating disks and non-thermal radiation processes impose further complications. Not surprisingly, all existing solutions made a number of approximations.

The simplest possible case, steady mass flux through the disk and black body emission perpendicular to it, leads to an expression for emitted flux proportional to $\nu^{1/3}$ at low frequencies [163] in rough accord with some real sources. The level of mass flux depends on viscosity through the disk. Molecular viscosity alone would leave sources invisibly faint (and the disks in place for more than the age of the universe). The correct physics is not known and is parametrized as a dimensionless constant, α . The viscosity assumed is then that constant fraction of the local sound speed times the disk thickness.

In addition to displaying a $\nu^{1/3}$ spectrum, such disks are geometrically thin, optically thick, large in radius, and small in total mass. They are also unstable to just about any sort of perturbation you care to impose [171,172].

Pringle [167] notes that the disks should not really be described as unstable, but rather as inconsistent. That is, if you assume a stationary disk with a given prescription for viscosity, cooling, etc., but find that thermal and viscous perturbations in it grow, then you have chosen the wrong viscosity (or something) and should try again. It is not known whether there are circumstances under which no viscosity law leads to stationarity.

Real disks do, in fact, change with time in several ways, and they are not (or at least not always) very thin. Transient X-ray enhancements in LMXRBs can be reproduced by disks switching between optically thick and thin, much like the process blamed for dwarf nova outbursts [173-175]. The high and low states of Cyg X-1 may have a similar explanation [176].

Dips and other structure in X-ray light curves imply that some disks are both thick and structured [11] and that this extended part can come and go in hours [177]. The extreme version of such extended material is a hot accretion disk corona [178], as implied by some models for X-ray spectra and variability. Just how the corona is heated is under debate [179,180], but if heating is an intrinsic part of the viscosity transport mechanism, then as much as half of the disk gas may be carried off in the corona and winds rather than accreting onto the neutron star [181].

A disk need not necessarily form in systems where a neutron star accretes material from the wind of a massive companion. Anything passing within about $R = 2GM/V^2$ of an accretor of mass M (V = wind speed) will be swept up. The neutron stars in wind-fed systems typically have strong fields. Thus the accretion process is dominated by channelling along the field lines [182-184]. The process is sufficiently simple that the X-ray variability tells us

something about wind structure (White [14] on X1700-37).

Relatively small, typically transient disks are, however, the most likely explanation for assorted optical and X-ray features and variability in some massive systems [185,186]. In systems with Be donors and eccentric orbits, the neutron star is likely to pick up a disk at closest approach [187]. Not surprisingly, gas flow patterns are complicated when both disk and magnetic field are important [188].

The standard black hole candidate systems probably also have accretion disks on two grounds. First, radial accretion straight into the black hole is likely to send all the energy down inside, so we would not observe diskless systems. Second, some of the variability is most readily modeled as disk instabilities [189,190].

6. Peculiar or puzzling phenomena and objects

6.1. Quasi-periodic oscillations (QPOs)

Many astronomical phenomena persist for a few to a few hundred of their own periods and so could be described as quasi-periodic. The kind of question here (elegantly reviewed by the co-discoverer, van der Klis [191]) occurs, mostly, in the X-ray flux of low mass XRBs. Some systems also display bursts, orbital modulation, and other variability establishing their identity as binaries.

Typical properties include frequencies of 5–60 Hz, widths (in the power spectrum) of about half the central frequency, amplitudes of 1–10%, persistence for $\geq 10^5$ cycles, and remarkably complex (but repeatable, describable, and arguable explainable) correlations of their properties with the source brightnesses and colour temperatures [192,193]. Interesting behaviour and correlations carry across to ultraviolet, optical, and radio fluxes [194–197].

Some well-studied sources, including Cyg X-2, Sco X-1, and GX17 + 2, present (at least) two discrete modes, associated with different spectral states [198,199]. The globular cluster source 1820-30 in NGC 5547 [200] displays different correlations, which may or may not amount to discrete modes. Extra noise comes and goes, only partly correlated with the quasi-periodic oscillatory (QPO) modes [201]. A complete model needs also to account for this noise.

The quasi-period of one mode is nicely modelled as a beat frequency between the rotation periods of the inner edge of the accretion disk and of the magnetosphere of the neutron star. Variability occurs because clumps of gas find it easier to enter the magnetosphere at its poles (tipped relative to the rotation poles [202]). Changes in rate of gas accretion from disk to neutron star dominate mode switches and other variations [194,203].

The beat model does not account well for other modes [199]. An instability in the accretion disk or process itself has many advocates. Possibilities include the marginally stable orbit at $r = 6GM/c^2$ [204], an accretion disk corona [205], Rayleigh–Taylor instabilities of gas already in the magnetosphere [161], and a one-armed spiral mode in the disk [206].

If the beat model is correct for one mode, then the observed periods confirm our expectation that old neutron stars in LMXRBs should have been spun up by accretion to millisecond periods. The added mass in some cases must be a fair fraction of a solar mass. Thus the eventual disentanglement of QPO properties should allow us to investigate neutron stars and their equations of state over a wide range of masses and radii.

An examination of massive XRBs finds all sorts of variability, but no tidy correlations like those in the low mass systems [207]. Phenomena probably related to QPOs occur in (a) the black hole candidate system LMC X-1 [208], (b) the 1983 August 1 gamma ray burster [209], (c) the rapid burster [210], and (d) several massive XRBs [191]. GX 2030 + 375 [211] is particularly instructive. Assuming the beat model, the QPO frequency of 0.2 Hz and the known period of rotation of the neutron star (42 s) permit one to calculate the size of the magnetosphere. The required surface dipole field of the neutron star is then 10^{12-13} G, just as you expected, providing some support for the model.

6.2. SS 433

The 433rd object in a catalogue of emission line objects compiled by Stephenson and Sanduleak is also an X-ray source that has earned good reviews [212,213] and even its very own conference [214]. Narrow emission lines of hydrogen and helium display a stable period of 13.1 days at an amplitude of 195 km s^{-1} [215] demonstrating its binary nature. But the really interesting velocity variations belong to wider red and blue shifted Balmer emission lines, which have a period of 164 days and an amplitude of $\pm 40\,000 \text{ km s}^{-1}$.

These velocities were quickly (and stably) modelled as a pair of oppositely directed jets, moving at 0.26c in directions that precess every 164 days around an axis tilted at 79° to the plane of the sky [3,216]. The kinetic energy flux in the jets is about $10^{39} \text{ erg s}^{-1}$. This is probably the primary energy source for the surrounding nebula, W50, which is usually catalogued as a supernova remnant [217]. An additional energy source is probably needed [218] unlike the case of the Crab Nebula.

Several fairly major points still need to be sorted out. First is whether the X-ray component is massive enough to warrant identification as a black hole [219–221]. The difficulty is that we cannot be sure that any of the

emission lines really track the centre of mass of one star or the other [222].

Second, the jet velocity [(for which $v/c = (1216 - 912)/1216$)] certainly acts as if line locking via radiation pressure is in operation, but we do not really understand either the acceleration or the collimation of the jet [223,224]. And third, the nature of the instability that drives the jet precession is uncertain [213,215]. Data on even one other similar object would surely help a great deal, but fairly intense efforts to find one have so far failed.

6.3. PSR 1957 + 20

The binary pulsar 1957 + 20 is informative in two ways. First, with its orbit period of 9.17 h and its companion mass of only about $0.02 M_{\odot}$ [225], it is the logical outcome of processes occurring in low mass X-ray binaries such as Cyg X-3 and 1820-30 [226,227]. What little remains of the companion is probably degenerate helium, illuminated by the pulsar to give rise to the optical and infrared light curves seen [228-230].

Second, the pulsar period, at 1.6 ms, is the same as that of the fastest single pulsar, suggesting that this may be the minimum possible for neutron stars and thereby telling us that the correct equation of state is not the extremely soft sort needed to make possible still more rapid rotation.

The pulsar is eclipsed for about 50 min out of each orbit period; and herein lies the puzzle. The occulter must be a good deal larger than its Roche lobe would let the star be. A wind largely opaque to radio waves of all frequencies must be evaporating off the companion, though it is not entirely clear that the available energy can actually do this [231,232]. The implied life expectancy is only about 10^8 yr [233]. An upper limit to the decay rate of the orbit says that 1957 + 20 will be with us for at least 10^7 more years [225].

The discovery of psr 1744 + 24A in the globular cluster Terzan 5 bridges part of the gap between 1957 + 20 and other systems. Its orbit period is only 110 min, and the 50 min eclipses imply a similarly extended occulter. The radio emission occasionally disappears completely for several orbits, followed by evidence for stray gas in the vicinity (increased dispersion of pulses at low frequencies). The companion mass is at least $0.09 M_{\odot}$ leading to a longer life expectancy than for the prototype, and this source provides considerable confirmation of the basic evaporating wind model [234].

Hertz *et al.* [67] have pointed to GX 9 + 1 as a possible transition object from X-ray binary to millisecond pulsar, but their search of EXOSAT data found no short-period X-ray pulsations down to 1% amplitude. In any case, two known members of the class

will be left as single millisecond pulsars by the disappearance of their companions in much less than the age of the universe.

6.4. TeV and PeV gamma ray sources

Neutral particles above 10^{12} eV hitting the earth's atmosphere make flashes of Cerenkov light, and those above 10^{15} eV give rise to extensive air showers (hadron primary particles being distinguishable from photons by the shapes of the light cones and the fractions of muons in the showers). Detectors for one or both of these operate on every continent. Recorded events have been associated with X-ray binaries as well as a handful of single pulsars [235,236]. Because the angular resolution is rather poor for each technique, identifications generally rest on phasing of the events with known rotation or orbital periods. Suggested binary neutron star sources, ordered roughly by decreasing persuasiveness of the evidence, include Cyg X-3, Her X-1, Vela X-1, 4U 0115 + 53, and 1822-37 [237].

The primary difficulty is that, while high energy events from the Crab pulsar act like photons [238], the PeV [239, 240] and probably the TeV ones [241] from the X-ray binaries act more like hadrons, producing muon rich air showers and other peculiar signatures. No known hadron can possibly get from there to here intact without getting hopelessly entangled in the galactic magnetic field. One must invoke either new physics or new particles (for which the name Cygnets was coined, but seems happily to have fallen out of use) or decline to believe the data. Curiously, getting some kind of entity up to these very high energies does not seem to be particularly difficult. At any rate, a number of theorists say they know how [242-247]. Admittedly they know different ways.

Cyg X-3, the most thoroughly studied source, emits at a fixed phase in its 4.8 h cycle and displays a 12.6 ms period not seen at other wavelengths [248-251]. It is turned off a large fraction of the time [252,253].

Her X-1 has an independently known X-ray rotation period, slightly longer than the one shown by the high energy particles [254,255]. Vela X-1 behaves similarly [256,257]. Still less is known about 4U 0115 and 1822 + 53 [258]. The period differences and the intermittency of the emission can be plausibly explained [259]. The real difficulty lies in understanding the nature of the primary high energy particles.

6.5. CTB 109 = E2259 + 586 (the Fahlman-Gregory object) and related sources

The Crab and a few other X-ray pulsars are definitely single neutron stars, radiating away their rotational

kinetic energy, and do not belong here. E2259 + 586 is, uniquely, a compact pulsating X-ray source [260] in a supernova remnant (CTB 109) which cannot be powered this way. With its rotation period of 6.98 s [261] and slow-down time of 3×10^5 yr [262], pulsar-type emission would amount to only 4×10^{32} erg s⁻¹ of the more than 10^{35} erg/s⁻¹ seen in X-rays; and the implied magnetic field would be 10^{14} G (not physically impossible, but unprecedented).

Thus the standard model is that of an accretion-powered X-ray source, despite the absence of any direct evidence for a visible companion and a maximum possible mass of $0.13 M_{\odot}$ for such a companion from the absence of orbital Doppler shifts in the neutron star rotation period [263, 264]. Paczyński [7] has recently proposed that the energy source is really a massive, rapidly rotating, magnetic white dwarf, produced by a merged pair of white dwarfs that failed to explode as a type I supernova. The radiation mechanism would then be analogous to the magnetic dipole radiation of pulsars. A little more than 1% of the available power is needed for the X-rays and (as in the Crab Nebula) a good deal of the rest is presumably fed into the surrounding supernova remnant. The X-ray emission mechanism is uncertain, but if the newly merged star is hot enough, thermal X-rays are possible.

H 0253 + 193 is smack dab in the middle of the nearest molecular cloud, Lynds 1457. Like the Fahlman-Gregory object, it shows an apparent rotation period (206 s) and no evidence for a companion. A single neutron star accreting from its dense surroundings is a possible model [265]; a cataclysmic binary (white dwarf accreting from companion) is a bit more likely; and a single, rotating, accreting, magnetic white dwarf is possible too. But the superposition of source on cloud is quite improbable for any of these explanations [266].

6.6. Gamma ray bursters and Geminga

These undoubtedly exist but probably do not belong in this paper. Gamma-ray detectors above the earth's atmosphere record events at the rate of a few per day with properties that include (a) duration of 0.05–100 s, (b) continuous spectra that look thermal with $kT = 30$ –300 keV, (c) spectral features including emission near 400 keV and absorption at 20–60 keV in many, (d) temporal structure with anything from a single peak to very complex subpulses down to 10 ms [267], (e) fluences such that the sources, if distributed through the galaxy, must peak at close to their Eddington luminosities (maximum permitted by radiation pressure [268]), (f) isotropy over the sky, and (g) remarkably low limits on an associated steady source at any wavelength.

Temperatures and time scales strongly suggest some

kind of neutron star origin, and the 20–60 keV features have been interpreted as cyclotron resonances, in magnetic fields of 10^{12-13} G [128,129]. But, the evidence for a binary companion was very indirect. It derived from the need for a source of accreting gas to undergo nuclear reactions in a once-popular model and for stuff to reprocess gamma rays into flashes of optical photons reported at the positions (but not at the times) of some bursts [269]. Doubt has been cast both on the reality of some of these flashes [270,271] and on the association of others with the bursts [272].

More important, the nuclear flash model probably makes the sources brighter between flashes than current upper limits on X-rays permit [273]. Hence a new generation of models invoke (a) crustal overturns in single neutron stars accreting gas from the interstellar medium [274] or (b) comets from the star's own or some other star's Oort clouds hitting an old neutron star [275,276] or just possibly, (c) mergers of neutron star binaries in distant galaxies, in which case gamma ray bursters are part of our subject matter, but not much else can be said at the moment [277].

Geminga, which is both the *Gemini* gamma ray source and Milanese dialect for 'it does not exist', has the smallest error box of the compact, steady gamma ray sources not obviously identified with known pulsars or X-ray binaries. Within that error box, there is only one interesting X-ray source, 1E 0630 + 178. The X-ray and γ -ray objects share a (rather tentative) period near 60 s, which may be lengthening on a time scale of only 1000 yr. Absence of X-ray absorption indicates a distance of no more than 100–200 pc. Even the faintest known low-mass X-ray binary at this distance would be more than 10^5 times brighter than the brightest peculiar star in the X-ray error box (a 25th magnitude blue star [278,279]). The ratio of X-ray to optical luminosity must be more than 1000, and the compactness of at least the X-ray source strongly implies some sort of neutron star configuration. Both single and binary models have been suggested [279,280], but none is terribly persuasive, and the object may not belong in this paper.

6.7. Extragalactic X-ray sources

No new kinds of things have turned up among the extragalactic binaries with compact components, but there are probably some population differences. Numbers of sources as a function of luminosity vary among the nearby spiral galaxies M33, M101, and M31 [281]. M31 (the Andromeda Nebula) apparently has a larger fraction of its X-ray luminosity coming from low mass systems than does the Milky Way [282], and its globular clusters are more likely to have sources brighter than 10^{37} erg s⁻¹ [283]. The two tentative optical identifica-

tions [284] are equally divided between high and low mass stars.

The recurrent transient source 0538-66 in the Large Magellanic Cloud brightens above 10^{39} erg s⁻¹, beyond anything in the Milky Way [285,286], and its rotation period of 0.069 s has only recently been bested by a galactic source at 0.06 s [287]. That the known LMC low-mass systems (LMC X-2, CAL 83, CAL 87) are all rather bright is presumably just a selection effect [288]. But that this small satellite of our own galaxy should contain a third to a half of the persuasive black hole candidates (LMC X-3 and X-1) is more surprising, though of low statistical significance.

The inventory in the Small Magellanic Cloud includes one pulsating (massive) source and a couple of transients, all with probable optical identifications [8]. One tentative optical counterpart of an X-ray source in M33 varies with a plausible 1.78 day period [289].

7. Concluding Remarks

The author feels a considerable affection for the present subject, her very first post-doctoral paper (V. Trimble and K. S. Thorne 1969, *Astrophys. J.*, **156**, 1013) having reported on a search for binary systems with collapsed companions (neutron star or black hole). We did not find any. The critical event in discovering such systems was the launch of the Uhuru X-ray satellite, which returned positions for many X-ray sources accurate enough to permit routine optical identification. Reliable orbits from a combination of optical and X-ray data followed. The discovery of the binary and millisecond pulsars also arose out of a technological advance that permitted scanning very large quantities of data across time and frequency domains to look for pulses that would otherwise be completely smeared out by interstellar propagation and/or orbit effects. The very rapid expansion of the inventory of these objects in the last year or two has surprised even the observers reporting them.

Most of the puzzling objects and phenomena mentioned in section 6 have also surfaced as a result of expansion of the range of observables—to higher time resolution, harder or softer photons, fainter sources, and so forth. Thus it is that astronomers are forever asking their paymasters for more and bigger and stronger. Many (not all) of the unanswered questions in the previous sections suggest rather definite kinds of observations. For instance, the Gamma Ray Observatory and other satellites scheduled for the 1990s really should count and pinpoint enough gamma ray bursts to tell us whether they are within the plane of the Milky Way or at cosmological distances. And any one of the new X-ray binaries currently being found by Ginga has

a chance of being another SS 433, while ROSAT in its first few months of operation has catalogued enough sources to keep ground-based follow-up going for years looking for additional examples of interesting kinds of sources and, occasionally, finding a new category that nobody had expected. Please stay tuned!

References

- [1] Trimble, V., and Rees, M. J., 1971, *Astrophys. J.*, **166**, L85.
- [2] van den Heuvel, E. P. J., 1981, *IAU Symp.*, **93**, 155.
- [3] Fabian, A. C., and Rees, M. J., 1979, *Mon. Not. Royal Astron. Soc.*, **187**, 1p.
- [4] Emmering, R. T., and Chevalier, R. A., 1989, *Astrophys. J.*, **345**, 931.
- [5] Bisnovatyi-Kogan, G. S., 1990, *Astrofiz.*, **31**, 751.
- [6] Lattimer, J. M., and Schramm, D. N., 1974, *Astrophys. J.*, **192**, L145.
- [7] Paczynski, B., 1990, *Astrophys. J.*, **363**, 218.
- [8] Bradt, H. V., and McClintock, J. E., 1983, *Ann. Rev. Astron. Astrophys.*, **21**, 13.
- [9] Nagase, F., 1989, *Publ. Astron. Soc. Japan.*, **41**, 1.
- [10] van Oijen, J. G. J., 1989, *Astron. Astrophys.*, **217**, 115.
- [11] Parmar, A. N., and White, N. E., 1988, *Mem. Ital. Astron. Soc.*, **59**, 147.
- [12] Rappaport, S. J., et al., 1989, *Astrophys. J.*, **345**, 203.
- [13] Sahade, J., McCluskey, G., and Kondo, Y., (eds), 1991, *Interacting Binaries* (in press).
- [14] White, N. E., 1989, *Astron. Astrophys. Rev.*, **1**, 85.
- [15] van den Heuvel, E. P. J., and Habets, G. M. H. J., 1985, in: *Supernovae, Their Progenitors, and their Remnants*, edited by G. Srinivasan and V. Radhakrishnan (Indian Academy of Sciences, Bangalore) p. 129.
- [16] Vanbeveren, D., 1989, *Astron. Astrophys.*, **224**, 93.
- [17] Leahy, D. A., 1990, *Mon. not. Royal Astron. Soc.*, **242**, 188.
- [18] Priedhorsky, W. C., and Holt, S. S. 1987, *Space Sci. Rev.*, **45**, 291.
- [19] Makishima, K., et al., 1990, *Publ. Astron. Soc. Japan.*, **42**, 295.
- [20] Whitlock, L., et al. 1989, *Astrophys. J.*, **338**, 381.
- [21] Taam, R. E., and Fryxell, B. A., 1988, *Astrophys. J.*, **331**, L117.
- [22] Lyuti, V. M., et al., 1989, *Sov. Astron. Lett.*, **15**, 183.
- [23] Makishima, K., et al., 1988, *Nature.*, **373**, 746.
- [24] Ghosh, P., and Lamb, F. K., 1978, *Astrophys. J.*, **223**, L83.
- [25] Taam, R. E., and Fryxell, B. A., 1989, *Astrophys. J.*, **339**, 297.
- [26] Raubenheimer, B. C., and Ogelman, H., 1990, *Astron. Astrophys.*, **230**, 27.
- [27] Sakao, T., et al., 1990, *Mon. Not. Royal Astron. Soc.*, **246**, 11p.
- [28] Clark, G. W., et al., 1990, *Astrophys. J.*, **353**, 274.
- [29] Leahy, D. A. and Matsuoka, M. 1990, *Astrophys. J.*, **355**, 627.
- [30] Leonard, P. J. T., and Duncan, M. J., 1989, *Astron. J.*, **99**, 608.
- [31] Khruzina, T. S., and Cherepashchuk, A. M., 1986, *Sov. Astron.*, **30**, 422.
- [32] van den Heuvel, E. P. J., 1986, in: *The Evolution of Galactic X-ray Binaries*, edited by J. Truemper, W. Lewin and W. Brinkman (Dordrecht: Reidel), p. 107.
- [33] Narayan, R., 1987, *Astrophys. J.*, **319**, 162.
- [34] Takeuchi, Y., et al., 1990, *Publ. Astron. Soc. Japan.*, **42**, 295.
- [35] Koyama, K., et al., 1990, *Nature.*, **343**, 148.
- [36] Makino, F., et al., 1990, *IAU Circular* 4967.
- [37] Kapusta, J. I., and Olive, K. A., 1990, *Phys. Rev. Lett.*, **64**, 14.
- [38] Bahcall, S., et al., 1990, *Astrophys. J.*, **362**, 251.
- [39] Fabian A. C., et al., 1989, *Mon. Not. Royal Astron. Soc.*, **238**, 729.
- [40] Dolan, J. F., and Tapia, S. 1989, *Astrophys. J.*, **344**, 830.
- [41] Sokolov, V. V., 1988, *Sov. Astron.*, **31**, 47.

- [42] Barr, P., and van der Woerd, H., 1990, *Astrophys. J.*, **352**, L41.
- [43] Hameury, J.-M., King, A. R., and Lasota, P., 1990, *Astrophys. J.*, **353**, 585.
- [44] Kitamura, S., et al., 1990, *Astrophys. J.*, **361**, 590.
- [45] Ilovaisky, S. A., 1988, *Mem. Ital. Astron. Soc.*, **59**, 221.
- [46] Steinman-Cameron, T., et al., 1990, *Astrophys. J.*, **359**, 192.
- [47] Locher, J. C., et al., 1989, *Astrophys. J.*, **337**, 827.
- [48] Unno, W., et al., 1990, *Publ. Astron. Soc. Japan.*, **42**, 269.
- [49] Basani, L., et al., 1989, *Astrophys. J.*, **343**, 313.
- [50] Bucharev, N. G., et al., 1988, *Sov. Astron.*, **32**, 405.
- [51] Kuiper, L., et al., 1988, *Astron. Astrophys.*, **203**, 79.
- [52] Dolan, J. F., and Tapia, S., 1990, *Publ. Astron. Soc. Pacific*, **101**, 1135.
- [53] Haswell, C. A., and Shafter, A. W., 1990, *Astrophys. J.*, **359**, L47.
- [54] de Kool, M., et al., 1987, *Astron. Astrophys.*, **193**, 47.
- [55] Tsunemi, et al., 1989, *Astrophys. J.*, **337**, L81.
- [56] Cowley, A. P., et al., 1990, *Astrophys. J.*, **350**, 288.
- [57] Pavlenko, E. P., et al., 1989, *Sov. Astron. Lett.*, **15**, 262.
- [58] Ritter, H., 1990, *Astron. Astrophys.*, Suppl. **85**, 1179.
- [59] Milgrom, M., 1978, *Astron. Astrophys.*, **67**, L25.
- [60] Dotani, T., et al., 1990, *Nature*, **347**, 534.
- [61] Soong, Y., 1990, *Astrophys. J.*, **348**, 634.
- [62] Bisnovatyi-Kogan, G. S., et al., 1990, *Sov. Astron.*, **34**, 44.
- [63] Truemper, J., et al., 1986, *Astrophys. J.*, **300**, L63.
- [64] Mihara, T., et al., 1990, *Nature*, **346**, 250.
- [65] Levine, A., et al., 1988, *Astrophys. J.*, **327**, 753.
- [66] Shvartsman, V. F., et al., 1989, *Soviet Astron. Lett.*, **15**, 532.
- [67] Hertz, P., et al., 1990, *Astrophys. J.*, **354**, 267.
- [68] Asaoka, I., and Hoshi, L., 1989, *Publ. Astron. Soc. Japan.*, **41**, 1049.
- [69] Velusamy, T., and Subrahmanya, C. R., 1989, *Mon. Not. Royal Astron. Soc.*, **239**, 281.
- [70] Strom, R. G., et al., 1989, *Nature*, **337**, 234.
- [71] Achterberg, A., 1989, *Nature*, **342**, 51.
- [72] Hellier, C., et al., 1990, *Mon. Not. Royal Astron. Soc.*, **244**, 39p.
- [73] Chevalier, et al., 1989, *Astron. Astrophys.*, **210**, 114.
- [74] Tavani, M., et al., 1989, *Astrophys. J.*, **21**, 1204.
- [75] Joss and Rappaport, 1979, *Astron. Astrophys.*, **71**, 217.
- [76] Margon, B., and Cannon, R., 1989, *Observatory*, **109**, 82.
- [77] Bailyn, C. D., et al., 1989, *Astrophys. J.*, **344**, 787.
- [78] Cudworth, K. M., 1988, *Astrophys. J.*, **96**, 105.
- [79] Lehto, H. J., et al., 1990, *Nature*, **347**, 49.
- [80] Nieto, J.-L., et al., 1990, *IAU Circular* 4944.
- [81] Clark, G. W., 1975, *Astrophys. J.*, **199**, L143.
- [82] Fabian A. C., Pringle, J. E., and Rees, M. J., 1975, *Mon. Not. Royal Astron. Soc.*, **187**, 1p.
- [83] Chernoff, D. F., and Weinberg, M. D., 1990, *Astrophys. J.*, **351**, 121.
- [84] Lewin, W. H. G., and Joss, P. C., 1983, in: *Accretion Driven X-ray Sources*, edited by W. H. G. Lewin and E. P. J. van den Heuvel (Cambridge: Cambridge University Press), p. 41.
- [85] Bailyn, C. D., and Grindlay, J. E., 1990, *Astrophys. J.*, **353**, 159.
- [86] McMillan, S. L., et al., 1990, *Astrophys. J.*, **354**, 190.
- [87] van den Heuvel, E. P. J., and Taam, R. E., 1984, *Nature*, **309**, 234.
- [88] Kulkarni, S., Narayan, R. and Romani, R., 1990, *Astrophys. J.*, **356**, 174.
- [89] Narayan, R., and Popham, R., 1989, *Astrophys. J.*, **341**, L25.
- [90] Canal, R., et al., 1990, *Astrophys. J.*, **356**, L51.
- [91] Kaluzny, J., 1988, *Acta Astron.*, **38**, 207.
- [92] Cowley, A. P., and Schmidtke, P. L., 1990, *Astron. J.*, **99**, 678.
- [93] Grindlay, 1988, *IAU Symp.*, **126**, 347.
- [94] Phinney and Kulkarni, 1990, preprint.
- [95] Hulse, R. A., and Taylor, J. H., 1975, *Astrophys. J.*, **195**, L51.
- [96] Backer, D. C., et al., 1982, *Nature*, **300**, 615.
- [97] Alpar, M. A., et al., 1982, *Nature*, **300**, 728.
- [98] Taylor, J. H., 1987, *IAU Symp.*, **125**, 383.
- [99] Verbunt, F., et al., 1989, *Mon. Not. Royal Astron. Soc.*, **241**, 51.
- [100] Tavani, M., 1989, *Bull. Amr. Astron. Soc.*, **21**, 1204.
- [101] Johnson, H. M., and Kulkarni, S., 1990, *Astrophys. J.*, (submitted).
- [102] Kulkarni, S., et al., 1990, *Astrophys. J.*, **363**, L5.
- [103] Kato, S., 1989, *Publ. Astron. Soc. Japan.*, **41**, 745.
- [104] Rees, M. J., 1986, *IAU Symp.*, **119**, 1.
- [105] Blandford, R. D., 1986, *IAU Symp.*, **119**, 359.
- [106] Kormendy, J., 1987, *IAU Symp.*, **127**, 17.
- [107] Taylor, J. H., and Weisberg, J. M., 1989, *Astrophys. J.*, **345**, 434.
- [108] Trimble, V., 1987, in: *High Energy Phenomena around Compact Stars*, edited by F. Pacini (Dordrecht: Reidel).
- [109] Rawley, et al., 1989, *Science*, **238**, 761.
- [110] Backer, D. C., and Hellings, R. W., 1986, *Ann. Rev. Astron. Astrophys.*, **24**, 537.
- [111] Weisberg, J. M., Romani, R., and Taylor, J. H., 1989, *Astrophys. J.*, **347**, 1030.
- [112] Anderson, S. G., et al., 1990, *Nature*, **346**, 42.
- [113] Glendenning, N. K., 1989, *Phys. Rev. Lett.*, **63**, 2629.
- [114] Miralda-Escude, J., et al., 1990, *Astrophys. J.*, **362**, 572.
- [115] Magnier, E., et al., 1989, *Mon. Not. Royal Astron. Soc.*, **237**, 729.
- [116] Nakamura, N., et al., 1988, *Publ. Astron. Soc. Japan*, **40**, 209.
- [117] Kaminker, A. D., et al., 1988, *Sov. Astron.*, **32**, 392.
- [118] Damen, E., 1989, *Mon. Not. Royal Astron. Soc.*, **237**, 523.
- [119] Pennix, W., 1989, *Astron. Astrophys.*, **208**, 146.
- [120] Haberl, F., 1987, *Astrophys. J.*, **314**, 266.
- [121] Blandford, R. D., Applegate, J. H., and Hernquist, L., 1983, *Mon. Not. Royal Astron. Soc.*, **204**, 1025.
- [122] Lyne, A. G., Manchester, R. N., and Taylor, J. H., 1985, *Mon. Not. Royal Astron. Soc.*, **213**, 613.
- [123] Haensel, P., 1990, *Astron. Astrophys.*, **229**, 133.
- [124] Taam, R. E., and van den Heuvel, E. P. J., 1986, *Astrophys. J.*, **305**, 325.
- [125] Verbunt, F., et al., 1990, *Astron. Astrophys.*, **234**, 195.
- [126] Srinivasan, G., et al., 1990 *Current Sci.*, **59**, no. 1.
- [127] Sang, Y., and Channugam, G., 1990, *Astrophys. J.*, **363**, 597.
- [128] Meszaros, P., et al., 1989, *Astrophys. J.*, **337**, L29.
- [129] Dermer, C. D., 1990, *Astrophys. J.*, **360**, 197.
- [130] Romani, 1990, *Nature*, **347**, 741.
- [131] Shibasaki, N., et al., 1989, *Nature*, **342**, 656.
- [132] Rankin, J. M., and Gil, J. A., 1989, *Comments on Astrophys.*, **14**, 1.
- [133] Taylor, J. H., and Stinebring, D., 1986, *Ann. Rev. Astron. Astrophys.*, **24**, 285.
- [134] Ho, C., 1989, *Astrophys. J.*, **342**, 396.
- [135] Michel, F. C., 1982, *Rev. Mod. Phys.*, **54**, 1.
- [136] Ruderman, M. A., and Sutherland, P. G., 1975, *Astrophys. J.*, **196**, 51.
- [137] Sedrakyan, D. M., 1989, *Astrofiz.*, **31**, 101.
- [138] Wang, D., et al., 1989, *Astrophys. Space Sci.*, **161**, 271.
- [139] Kirk, J. G., and Truemper, J. E., 1983, in: *Accretion Driven X-ray Sources*, edited by W. H. G. Lewin and E. P. J. van den Heuvel (Cambridge: Cambridge University Press), p. 261.
- [140] Alexander, S. G., 1989, *Astrophys. J.*, **342**, 928.
- [141] Litvinchuk, A. A., 1989, *Sov. Astron.*, **33**, 381.
- [142] Hirano, K., et al., 1987, *Publ. Astron. Soc. Japan.*, **39**, 19.
- [143] Dennerl K., 1990, in: *ESLAB 1989: 23rd Eslab Symposium, ESA Special Publications* (in press).
- [144] Kallman, T. R., 1990, in: *ESLAB 1989: ESLAB Symposium, ESA Special Publications* (in press).

- [145] Ponman, T. J., et al., 1990, *Mon. Not. Royal Astron. Soc.*, **246**, 287.
- [146] Vrtillek, S. K., et al., 1986, *Astrophys. J.*, **307**, 698.
- [147] Makishima, K., et al., 1989, *Publ. Astron. Soc. Japan.*, **41**, 531.
- [148] White, N. E., 1988, *Astrophys. J.*, **324**, 367.
- [149] Mitsuda, K., and Tanaka Y., 1986, in: *The Evolution of Galactic X-ray Binaries*, edited by J. Truemper, W. Lewin and W. Brinkmann (Dordrecht: Reidel), p. 195.
- [150] Burnard, et al., 1990.
- [151] Hirofani, K., et al., 1990, *Astrophys. J.*, **355**, 577.
- [152] Hanawa, T., 1990, *Astrophys. J.*, **355**, 585.
- [153] White, N. E., 1989, in *Theory of Accretion Disks*, edited by F. Meyer et al., (Dordrecht: Kluwer), p. 189, F. Meyer et al. (1989) p. 269.
- [154] Grindlay, J. E., et al., 1976, *Astrophys. J.*, **205**, L127.
- [155] Joss, P. C., 1978, *Astrophys. J.*, **225**, L123.
- [156] Motch, C., et al., 1989, *Astron. Astrophys.*, **219**, 158.
- [157] Schoembs, R., and Zoeschinger, G., 1990, *Astron. Astrophys.*, **227**, 105.
- [158] Nakamura, N., et al., 1989, *Publ. Astron. Soc. Japan.*, **41**, 617.
- [159] van Paradijs, J., Pennix, W., and Lewin, W. H. G., 1988, *Mon. Not. Royal Astron. Soc.*, **233**, 437.
- [160] Gottwald, M., et al., 1989, *Astrophys. J.*, **339**, 1044.
- [161] Hanami, N., 1988, *Mon. Not. Royal Astron. Soc.*, **233**, 423.
- [162] Wade, R. A., 1985, in: *Interacting Binaries*, edited by P. P. Eggleton and J. E. Pringle (Dordrecht: Reidel), p. 289.
- [163] Lynden-Bell, D., 1969, *Nature*, **223**, 690.
- [164] Smak, J., 1971, *Acta Astron.*, **21**, 15.
- [165] Prendergast, K. H., and Burbidge, G. R., 1968, *Astrophys. J.*, **151**, L83.
- [166] Shakura, N. I., and Sunyaev, R. A., 1973, *Astron. Astrophys.*, **24**, 429.
- [167] Pringle, J. E., 1981, *Ann. Rev. Astron. Astrophys.*, **19**, 137.
- [168] Petterson, J. A., 1983, in: *Accretion Driven X-ray Sources*, edited by W. H. G. Lewin and E. P. J. van den Heuvel (Cambridge: Cambridge University Press), p. 367.
- [169] Meyer, F., et al., (Eds.), 1989, *Theory of Accretion Disks*, (Dordrecht: Kluwer).
- [170] Treves, A., Maraschi, L., and Abramowics, M., (Eds), 1989, *Accretion* (Singapore: World Scientific).
- [171] Papaloizou, J. C. B., and Lin, D. N., 1989, *Astrophys. J.*, **344**, 645.
- [172] Blaes, O. M., and Hawley, J. F., 1988, *Astrophys. J.*, **326**, 277.
- [173] Huang, M., and Wheeler, J. C., 1989, *Astrophys. J.*, **343**, 229.
- [174] Mineshiga, S., and Wheeler, J. C., 1989, *Astrophys. J.*, **343**, 241.
- [175] Kakabari, K., et al., 1989, *Publ. Astron. Soc. Japan.*, **41**, 1035.
- [176] Hoshi, R., and Inoue H., 1988, *Publ. Astron. Soc. Japan.*, **40**, 421.
- [177] Smale, A. P., et al., 1988, *Mon. Not. Royal Astron. Soc.*, **232**, 642.
- [178] Kuperus, M., 1989, *Highlights Astron.*, **8**, 535.
- [179] Shaviv, G., and Wehrse, R., 1986, *Astron. Astrophys.*, **159**, L5.
- [180] Gnedin, Yu. N., and Khosanov, N. R., 1989, *Sov. Astron. Lett.*, **15**, 397.
- [181] Czerny, M., and King, A. R., 1989, *Mon. Not. Royal Astron. Soc.*, **241**, 839.
- [182] Lyubarskii, Yu. E., and Sunyaev, R. A., 1988, *Sov. Astron. Lett.*, **14**, 390.
- [183] Kraus, U., 1989, *Astron. Astrophys.*, **223**, 246.
- [184] Parmar, A. N., et al., 1989, *Astrophys. J.*, **338**, 373.
- [185] Haberl, F., and White, N. E., 1990, *Astrophys. J.*, **361**, 225.
- [186] Giovannelli, F., and Ziokowski, J., 1989, *Acta Astron.*, **40**, 95.
- [187] Sembay, S., et al., 1990, *Astrophys. J.*, **351**, 675.
- [188] Spruit, H. C., and Taam, R. E., 1990, *Astron. Astrophys.*, **229**, 475.
- [189] Asaoka, I., 1989, *Publ. Astron. Soc. Japan.*, **41**, 763.
- [190] Mineshiga, S., et al., 1990, *Astrophys. J.*, **358**, L5.
- [191] van der Klis, M., 1989, *Rev. Astron. Astrophys.*, **27**, 517.
- [192] Hasinger, G., and van der Klis, M., 1989, *Astron. Astrophys.*, **255**, 79.
- [193] Schulz, N. S., et al., 1989, *Astron. Astrophys.*, **225**, 48.
- [194] Hasinger, G., et al., 1990, *Astron. Astrophys.*, **235**, 131.
- [195] Hjellming, R. M., et al., 1990, *Astron. Astrophys.*, **235**, 147.
- [196] van Paradijs, J., et al., 1990, *Astron. Astrophys.*, **235**, 156.
- [197] Vrtillek, S. K., et al., 1990, *Astron. Astrophys.*, **235**, 131.
- [198] Hasinger, G., et al., 1989, *Astrophys. J.*, **337**, 843.
- [199] Pennix, W., et al., 1990, *Mon. Not. Royal Astron. Soc.*, **243**, 114.
- [200] Dotani, T., et al. 1989, *Pub. Astron. Soc. Japan.*, **41**, 427, 577.
- [201] Norris, J. P., et al., 1990, *Astrophys. J.*, **361**, 514.
- [202] Alpar, M. A., and Shaham, J., 1985, *Nature*, **362**, 239.
- [203] van der Klis, M., et al., 1990, *Astrophys. J.*, **360**, L19.
- [204] Paczyński, B., 1987, *Nature*, **327**, 300.
- [205] Stollman, G. B., and Kuperman, M., 1988, *Astron. Astrophys.*, **203**, 104.
- [206] Kato, S., 1990, *Publ. Astron. Soc. Japan.*, **42**, 99.
- [207] Bellini, T., and Hasinger, G., 1990, *Astron. Astrophys.*, **230**, 103.
- [208] Ebisawa, K., et al., 1989, *Publ. Astron. Soc. Japan.*, **41**, 519.
- [209] Kuznetsov, A. V., et al., 1987, *Sov. Astron. Lett.*, **13**, 445.
- [210] Dotani, T., et al., 1990, *Astrophys. J.*, **350**, 395.
- [211] Angelini, L., Stella, L., and Parmar, A. N., 1989, *Astrophys. J.*, **346**, 906.
- [212] Margon, B., 1983, in: *Accretion Driven X-ray Sources*, edited by W. H. G. Lewin and E. P. J. van den Heuvel (Cambridge: Cambridge University Press), p. 287.
- [213] Zwitter, T., et al., 1989, *Fund. Cosmic Phys.*, **13**, 309.
- [214] Beer, P., 1981, *Vistas in Astron.*, **25**, nos 1 and 2.
- [215] Margon, B., and Anderson, S. F., 1989, *Astrophys. J.*, **347**, 448.
- [216] Milgrom, M., 1979, *Astron. Astrophys.*, **76**, L3; **78**, L9; **78**, 617.
- [217] Grindlay, J. E., et al., 1983, *IAU Symp.*, **101**, 459.
- [218] Kochanek, C. S., and Hawley, J. R., 1990, *Astrophys. J.*, **350**, 561.
- [219] Antokhina, E. A., and Cherepashchuk, A. M., 1987, *Sov. Astron.*, **31**, 295.
- [220] Brinkmann, W., et al., 1989, *Astron. Astrophys.*, **218**, L13.
- [221] Kawai, N., et al., 1989, *Publ. Astron. Soc. Japan.*, **41**, 491.
- [222] Filippenko, A. V., 1988, *Astron. J.*, **96**, 242.
- [223] Liang, E., 1988, *Astrophys. J.*, **334**, 339.
- [224] Alodzhants, G. P., et al., 1989, *Astrofiz.*, **31**, 574.
- [225] Fruchter, A. J., et al., 1990, *Astrophys. J.*, **351**, 624.
- [226] Kluzman, W., et al., 1988, *Nature*, **334**, 225.
- [227] van den Heuvel, E. P. J., and van Paradijs, J., 1988, *Nature*, **334**, 227.
- [228] Kulkarni, S., Djorgovskii, S., and Fruchter, A. S., 1988, *Nature*, **334**, 524.
- [229] Callanan, P. J., et al., 1989, *Mon. Not. Royal Astron. Soc.*, **241**, 27p.
- [230] Eales, S. A., et al., 1990, *Mon. Not. Royal Astron. Soc.*, **242**, 17p.
- [231] Ruderman, M. A., Shaham, J., and Tavani, M., 1989, *Astrophys. J.*, **336**, 507.
- [232] Ruderman, M. A., Shaham, J., and Tavani, M., 1989, *Astrophys. J.*, **343**, 272.
- [233] Cheng, A. F., 1989, *Astrophys. J.*, **339**, 29.
- [234] Nice, D. J., et al., 1990, *Astrophys. J.*, **361**, L61.
- [235] Lamb, R. C., and Weekes, T. C., 1989, *Science*, **238**, 1528.
- [236] Shapiro, M. M., and Wefel, J. P., (Eds), 1989, *Cosmic Gamma Rays, Neutrinos and Related Astrophysics* (Dordrecht: Kluwer).
- [237] Agaronyan, F. A., et al., 1989, *Astrofiz.*, **31**, 534.
- [238] Weekes, T. C. et al., 1989, *Astrophys. J.*, **342**, 371.
- [239] Dingus, B. L., et al., 1988, *Phys. Rev. Lett.*, **61**, 1906.
- [240] Dingus, B. L., et al., 1988, *Phys. Rev. Lett.*, **60**, 1785.
- [241] Haines, T., et al., 1990, *14th Texas Symposium Relativistic*

- Astrophysics*, (New York: NY Academy of Science), in press.
- [242] Eichler, D., and Ko, K., 1988, *Astrophys. J.*, **328**, 179.
 - [243] Kiraly, P., and Meszaros, P., 1988, *Astrophys. J.*, **333**, 719.
 - [244] Berezhinski, V. S., 1988, *Nature*, **334**, 506.
 - [245] Schlickeiser, R., 1989, *Astron. Astrophys.*, **213**, L23.
 - [246] Harding, A. K., and Gaisser, T. K., 1990, *Astrophys. J.*, **358**, 561.
 - [247] Mitra, A. K., 1990, *Astron. Astrophys.*, **234**, L5.
 - [248] Brazier, K. T. S., et al., 1990, *Astrophys. J.*, **350**, 745.
 - [249] Gregora, A. A., et al., 1990, *Astron. Astrophys.*, **237**, L5.
 - [250] Cassiday, G. L., et al., 1989, *Phys. Rev. Lett.*, **62**, 383.
 - [251] Tonwar, S. C., et al., 1988, *Astrophys. J.*, **330**, L11.
 - [252] Alexandreas, D. E., et al., 1990, *Phys. Rev. Lett.*, **64**, 2973.
 - [253] Cassiday, G. L., et al., 1989, *Phys. Rev. Lett.*, **62**, 2329.
 - [254] Lamb, R. C., et al., 1988, *Astrophys. J.*, **328**, L13.
 - [255] Gupta, S. K., et al., 1990, *Astrophys. J.*, **354**, L13.
 - [256] Raubenheimer, B. C., et al., 1989, *Astrophys. J.*, **336**, 394.
 - [257] Carraminana, A., et al., 1989, *Astrophys. J.*, **346**, 967.
 - [258] Ciampa, D., Clay, R. W., and Edwards, P. G., 1989, *Astrophys. J.*, **346**, 151.
 - [259] Cheng, K. S., and Ruderman, M., 1989, *Astrophys. J.*, **337**, L77.
 - [260] Fahlman, G. C., and Gregory, P. C., 1981, *Nature*, **293**, 202.
 - [261] Carlini, A., and Treves, A., 1989, *Astron. Astrophys.*, **215**, 283.
 - [262] Koyama, K., et al., 1989, *Publ. Astron. Soc. Japan*, **41**, 483.
 - [263] Davies, S. R., et al., 1989, *Mon. Not. Royal Astron. Soc.*, **237**, 973.
 - [264] Davies, S. R., Wood, K. S., and Coe, M. J., 1990, *Mon. Not. Royal Astron. Soc.*, **245**, 268.
 - [265] Bhatt, H. C., 1990, *Astron. Astrophys.*, **232**, 367.
 - [266] Patterson, J., and Halpern, J. P., 1990, *Astrophys. J.*, **361**, 123.
 - [267] Mitrofanov, I. G., et al., 1990, *Sov. Astron. Lett.*, **16**, 129.
 - [268] Hartmann, D., et al., 1990, *Astrophys. J.*, **348**, 625.
 - [269] Hudek, R., et al., 1989, *Astron. Astrophys.*, **225**, 411.
 - [270] Greiner, J., et al., 1990, *A.N.*, **308**, 121.
 - [271] Zytlow, A. N., 1990, *Astrophys. J.*, **359**, 138.
 - [272] Schaefer, B., et al. 1987, *Sky and Telescope*, **73**, 604.
 - [273] Murakami, T., et al., 1990, *Astron. Astrophys.*, **227**, 451.
 - [274] Blaes, O., et al., 1990, *Astrophys. J.*, **363**, 612.
 - [275] Pineault, S., and Poisson, E., 1989, *Astrophys. J.*, **347**, 1141.
 - [276] Mitrofanov, I. G., and Sagdeev, R. Z., 1990, *Nature*, **344**, 313.
 - [277] Paczyński, B., 1990, *Astrophys. J. Lett.*, **365**, L9.
 - [278] Bignami, G., Caraveo, P. A., and Paul, J. A., 1988, *Astron. Astrophys.*, **202**, L1.
 - [279] Halperin, J. P., and Tytler, D., 1988, *Astrophys. J.*, **330**, 201.
 - [280] Bignami, G., 1987, in: *High Energy Phenomena around Collapsed Stars*, edited by F. Pacini (Dordrecht: Reidel), p. 297.
 - [281] Trinchieri, G., et al., 1990, *Astrophys. J.*, **356**, 110.
 - [282] Makishima, K., et al., 1989, *Publ. Astron. Soc. Japan*, **41**, 697.
 - [283] Long, K. S., and van Speybroeck, L. P., 1983, in: *Accretion Driven X-ray Sources*, edited by W. H. G. Lewin and E. P. J. van den Heuvel (Cambridge: Cambridge University Press), p. 117.
 - [284] Lollura, A., et al., 1990, *Astrophys. J.*, **356**, 119.
 - [285] Smale, A. P., and Charles, P. A., 1989, *Mon. Not. Royal Astron. Soc.*, **238**, 595.
 - [286] Stevens, I. R., 1989, *Mon. Not. Royal Astron. Soc.*, **232**, 199.
 - [287] Caraveo, P., et al., 1989, *Astrophys. J.*, **338**, 338.
 - [288] Callanan, P. J., et al., 1989, *Mon. Not. Royal Astron. Soc.*, **240**, 31p.
 - [289] Peres, G., et al., 1989, *Astrophys. J.*, **336**, 140.

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