NEUTRON STAR BINARIES, PULSARS, AND BURST SOURCES[1]

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ABSTRACT

Some important but as yet unresolved issues involving neutron star binaries, pulsars, and burst sources are described. Attention is drawn to the types of observations most likely to resolve them. Many of these observations are likely to be carried out during the next decade by one or more missions that have been approved or proposed. Missing so far is an opportunity to carry out sensitive flux measurements with an imaging detector and broad-band spectroscopic studies in the energy range 30-150 keV. There is also a need for soft X-ray and X-ray observations with an instrument which has arcminute angular resolution and an effective area substantially greater than that of ROSAT or EXOSAT.

I. INTRODUCTION

Many interesting and important questions about neutron star binaries, pulsars, and burst sources are still unanswered. As examples, twenty such questions are discussed in §II, together with the types of observations most likely to resolve them. Although plausible interpretations have been proposed for almost all interesting observations, and in many cases widely accepted, these interpretations are often based on very fragile evidence. Thus, our apparent understanding of such observations could be reversed very easily. Some of the questions considered are of this type. Key observations suggested by these questions are compared with the opportunities offered by approved and proposed missions in §III.

In discussing each question, I have referred to several of the most recent papers as well as one or two recent review articles. Where an appropriate review article is unavailable or unknown to me, I have provided more extensive references. Photons in the energy ranges 0.1-10, 2-60, and 30-150 keV are referred to as soft X-rays, X-rays, and hard X-rays, respectively. Spectroscopic studies are categorized as low-resolution ($E/\Delta E < 10$), moderate-resolution ($E/\Delta E \sim 10$-100), or high-resolution ($E/\Delta E > 100$).

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II. CURRENT ISSUES

a) Pulsing X-ray Sources

1. Are these sources disk-fed or wind-fed? -- By this I mean, does the neutron star accrete matter from a disk or from a more radial flow? In considering this question, one should not assume that a neutron star with a companion that is losing mass via a wind is necessarily wind-fed, since such a companion may transfer matter to the neutron star with sufficient angular momentum to form a disk. Furthermore, the initial phase of critical-lobe overflow of massive stars, which usually also have winds, is adequate to power the binary X-ray sources with orbital periods less than five days without smothering them, and leads to reasonable X-ray source lifetimes on the order of 10^4 - 10^6 yr (Paczyński 1976; Savonije 1978, 1979). The currently available evidence suggests that most pulsing X-ray sources are fed by accretion disks, although this conclusion is not yet secure (see Ghosh and Lamb 1979; Elsner, Ghosh, and Lamb 1980).

An answer to this question is important for understanding the mass transfer process in binaries, reprocessing of X-radiation within the accretion flow, the gross structure of the magnetosphere, and the behavior of the pulse frequency with time.

The types of observations most likely to furnish information that will help to provide the answer are high-resolution ultraviolet and soft X-ray spectroscopy, and X-ray timing studies. Ultraviolet and soft X-ray spectroscopy could sample the accretion flow at and outside the magnetospheric boundary, while timing studies could measure the specific angular momentum of the inflowing plasma. As an example of what may be possible with timing studies, Figure 1 shows the relationship between the pulse period, period derivative, and accretion luminosity predicted by the most detailed current theory of disk accretion. A sequence of measurements of these quantities which traced out a curve like those shown would confirm that the source in question was disk-fed and also determine its magnetic moment.

2. How do some sources reach long periods and why do such periods persist? -- The mechanisms by which the long-period pulsing X-ray sources were spun down initially is not yet clear, although several possibilities have been proposed (see Davies, Fabian, and Pringle 1979; Ghosh and Lamb 1979; Elsner, Ghosh, and Lamb 1980; and references therein). Long periods are most likely the result of alternating episodes of spin-up and spin-down. Further support for this hypothesis has recently been provided by the Hakucho observations of Vela X-1 shown in Figure 2, which reveal alternating episodes of spin-up and spin-down. In disk-fed sources, such behavior finds a natural explanation in the magnetic braking that occurs when the accretion rate falls (Ghosh and Lamb 1979; Elsner, Ghosh, and Lamb 1980). In wind-fed sources, such behavior might be explained by reversals in the circulation of the matter accreted by the neutron star.

Despite the profoundly different implications of these two explanations, it has so far not been possible to unambiguously identify the cause of alternating intervals of spin-up and spin-down in any long-period source. Thus, for example, the episodes seen in Vela X-1 may be due to accretion by the neutron star of vortices in the wind from its companion, but they are also consistent with spin-up and spin-down due to accretion from a disk, assuming variations in the mass accretion rate of a few percent; such small variations in the accretion rate are not inconsistent with the constraints on X-ray flux variations reported to date.

Answers to these two questions are important for understanding the rate of formation of neutron star binaries, the typical lifetimes of X-ray binaries, and the properties of pulsars formed from massive X-ray binaries.

Among the more promising observations with which to explore these questions are X-ray timing of the low states of the long period sources and long-term monitoring of their luminosity behavior by, for example, a sky monitoring experiment. In connection with the latter, it is worth noting that the behavior on time scales longer than one or two months is known only for a handful of sources. As an example of what is expected, Figure 3 shows the different relationship between the luminosity and pulse frequency predicted for disk-fed sources which have small luminosity variations, like those reported in Her X-1, and sources which exhibit short, intense flares, like those reported in A0535+26.

3. What are the causes of pulse period fluctuations? — The reasons for the pulse period fluctuations observed in Her X-1, Cen X-3, Vela X-1 and other sources could be due to fluctuations in the accretion torque acting on the crust, episodic unpinning of vortices in the neutron superfluid thought to interpenetrate the inner crust, repeated fracturing of the crust, or stochastic spin-up of the neutron superfluid expected in the core of the star (Lamb, Pines, and Shaham 1978; for a review, see Lamb 1979). At present it is not even known whether the observed period fluctuations are produced by processes outside or inside these stars.

Answers to this question could provide important information about fluctuations in the accretion flow or, alternatively, about the internal dynamics of neutron stars.

The most promising observational approach here is to look for correlations between the X-ray luminosity and the spin-up rate, since fluctuations in the accretion luminosity may accompany fluctuations in the accretion torque, whereas short-term fluctuations in the luminosity are not expected as a result of internal processes.

4. What are the respective roles of magnetospheric and surface plasmas in forming pulse shapes and spectra? — There is some evidence that both play a role. Thus, for example, the complex waveforms seen in A0535+26 and Vela X-1 (see Fig. 4) have been interpreted as the result of cyclotron scattering by streams of accreting plasma above the stellar surface (Elsner and Lamb 1976), while spectral features reported in Her X-1 (see Fig. 5), 4U0115+63 (Wheaton et al. 1979), and 4U1626-67 (Pravdo et al. 1979) have been interpreted as the result of cyclotron scattering or emission (for reviews, see Lamb 1977; Staubert et al. 1981; and Trumper 1982).

Theoretical work has so far focussed primarily on the role of plasma at the stellar surface (see, for example, Fig. 6 and Nagel 1981a,b; for a review, see Mészáros 1982), but plasma above the surface is also expected to play an important role (Lamb 1977), as is plasma near the magnetospheric boundary

(McCray and Lamb 1976; Basko and Sunyaev 1976; McCray et al. 1982).

Answers to this question are important for understanding the patterns of plasma flow within the magnetosphere, the characteristic flow velocities within the magnetosphere, magnetic field geometries, and the physical conditions in the emission regions. This is an extremely difficult theoretical problem, so observational guidance is especially important.

A key discriminant between magnetospheric and surface plasma is the time scale of fluctuations in the pulse waveform or spectral features. The dynamical time scale for plasma near the magnetospheric boundary is expected to be ~ 0.1 - 1 s, and anisotropies in the emission pattern or spectral features caused by plasma there are expected to show fluctuations on a similar time scale. In contrast, the dynamical time scale near the stellar surface is ~ 0.1 - 1 ms, and angular and spectral features produced by this plasma are expected to show fluctuations on this time scale. The magnetospheric plasma can probably be studied best by moderate resolution soft X-ray spectroscopy and high-resolution spectroscopy at the 7 keV iron lines, whereas the surface plasma can probably be studied best by phase-resolved spectroscopy at X-ray and hard X-ray energies.

5. What are the surface magnetic fields and dipole moments of these neutron stars? — Theoretical interpretation of the observed spin-up rates, assuming disk accretion, yields dipole moments in the range 10^{29} - 10^{31} G cm^3, although the actual value for any given source is uncertain (Ghosh and Lamb 1979). Estimates based on reported spectral features give field strengths ~ 4-6 x 10^{12} G in Her X-1 and ~ 2-3 x 10^{12} G in 4U0115+63, while the variations of pulse shape with energy in A0535+26 and Vela X-1 have been interpreted as the result of cyclotron scattering by plasma streams channeled by small-scale magnetic loops of strength ~ 1-2 x 10^{12} G at distances ~ 10^5-10^6 cm above the stellar surface (for references, see question 4, above).

More information on this issue is important for understanding the evolution magnetic fields in pulsars (see Lamb 1981a) and X- and gamma-ray burst sources (see below).

Measures of dipole field strengths can be obtained for stars which are disk-fed, if theoretical curves like those shown in Figure 1 are confirmed and a sufficient set of spin-up rates, pulse frequencies, and accretion luminosities are assembled for each source so that the particular curve followed by a given source can be determined. In some cases it may be possible to estimate surface magnetic field strengths using X-ray and hard X-ray observations of pulse waveforms and spectra, although the problem of interpreting these observations appears to be much more difficult than that of interpreting timing observations.

6. What is the equation of state of matter at very high densities? — A substantial effort during the past decade has led to significant observational constraints on the equation of state of neutron star matter (for reviews, see Baym and Pethick 1979; Pines 1980; Lamb 1981b). Thus, for example, it has been possible to rule out several of the softer equations of state that have been proposed. However, large uncertainties still remain.

A precise knowledge of the equation of state is important for identifying black hole candidates, since the only presently known property of black holes that distinguishes them from nonmagnetic neutron stars is their mass, which may exceed the maximum stable mass of neutron stars. The equation of state is, of course, also of interest for the information it provides about the interactions of hadrons in dense matter.

Further progress will require refinements in our understanding of a variety of aspects of pulsing and bursting sources and is likely to be slower. New measurements of the orbits of neutron star binary systems can make a substantial contribution. In this connection, it is worth remembering that the orbits of only about half of the known systems of this type have been measured accurately. Measurements of the thermal fluxes from neutron stars, like those described below (question 11), could also make an important contribution, since the cooling rate of a hot neutron star is sensitive to the equation of state.

7. What are the internal dynamical properties of neutron stars? -- So far, there is no evidence for internal degrees of freedom in neutron star X-ray sources (see Boynton 1981; Lamb 1981). This is puzzling, given the evidence for a weakly coupled superfluid neutron component in pulsars and the variety of internal degrees of freedom expected theoretically (Lamb, Pines, and Shaham 1978).

X-ray timing observations are the most promising approach here (see Lamb 1979). Figure 7 shows the very different power transfer functions for pulse frequency fluctuations of a neutron star with and without an internal, finite-frequency normal mode.

b) "Galactic Bulge Sources"

8. How are they formed and how do they evolve? -- The bright galactic bulge sources are widely believed to be binary systems formed by capture processes (see Lewin and Clark 1980). However, there is evidence that the majority of bulge sources which are not currently surrounded by globular clusters may require a mechanism of formation other than capture of a general field star by a compact object (Lightman and Grindlay 1982). Moreover, the evolution of a white dwarf binary system into a neutron star binary does not produce a source with the high X-ray luminosities observed (Rappaport, Joss, and Webbink 1982).

Why are globular cluster X-ray sources so much more common in M31 than in our own galaxy? Both in our galaxy and in M31, the globular cluster sources are grouped near the plane, suggesting that passage through the galactic plane plays an important role in forming or activating these sources.

The most promising approach to studying the formation and evolution of the "bulge" sources is to study their appearance in nearby galaxies using optical and X-ray instruments.

9. Why is there never more than one bright, compact X-ray source observed in a globular cluster? -- Lightman and Grindlay (1982) have shown that the data are not inconsistent with a probability of observing an X-ray source in a globular cluster which varies as the inverse of the time scale for two-body

binary formation, as would be expected if this is the formation process. Assuming that this is the formation process, they show further that only one X-ray source is to be expected in any one cluster. Direct evidence of the binary character of the globular cluster sources would help to secure this argument.

There are two promising approaches here: long-term monitoring of X-ray flux levels to discover the modulation with binary phase that must be present at some level, if these sources are indeed binaries, and optical and X-ray studies of nearby galaxies, such as M31.

10. How large are their surface magnetic fields? -- It has been widely argued that the reason no pulsations have been seen in these sources is that the magnetic fields of these neutron stars are extremely weak. Although this is a plausible hypothesis (see Lewin and Clark 1980), it becomes less comfortable when one notes that Her X-1, which is believed to be $\sim 10^8$ years old, apparently has a magnetic field that is still $\sim 5 \times 10^{12}$ G (see Lamb 1981a), that the most plausible explanation for the temporal "footprints" of the X-ray burst sources is channeling of fuel by magnetic fields, and that the two most promising models of gamma-ray bursters, episodic accretion and thermonuclear explosions on neutron stars which are presumably rather old, both require surface magnetic fields $\gtrsim 10^{12}$ G (see question 17). Thus, the answer to this question remains uncertain.

The question can be addressed by sensitive X-ray timing observations, to look harder for periodic flux variations, and sensitive X-ray and hard X-ray spectroscopy, to search for any evidence of magnetic fields manifested by spectral features.

c) Pulsars

11. What are the surface temperatures of pulsars? -- Pulsars are expected to have surface temperatures in the range $10^5 - 10^6$ K due to compressional heating when they were formed (see, for example, Van Riper and Arnett 1978; Bowers and Wilson 1980; Epstein and Pethick 1981; Richardson et al. 1982), bombardment of their surfaces by particles and gamma-rays (see, for example, Cheng 1981), heating of their interiors due to friction between the solid crust and the neutron liquid (see Greenstein 1981), and release of energy in crustal or core fracture events (see Pines, Shaham, and Ruderman 1972) or in episodes of vortex unpinning (see Alpar et al. 1981). Stimulated in part by the much more sensitive observations made possible by EINSTEIN, substantial improvements have recently been made in detailed calculations of neutron star cooling (Glen and Sutherland 1980; Van Riper and Lamb 1981; Gudmundsson, Pethick, and Epstein 1982; Richardson, et al. 1982) as well as in understanding which energy transport processes affect the results most strongly (Gudmundsson, Epstein, and Pethick 1982). Figure 8 shows a comparison of the theoretical cooling curves of Van Riper and Lamb with observations.

Important new results on neutron star surface emission have been obtained with the EINSTEIN observatory (for reviews, see Helfand, Chanan, and Novick 1980; Helfand 1981). Observations of about fifty supernova remnants, including seven remnants of historical supernovae, have placed stringent upper limits on the luminosities of any compact source in all but four. In the four remnants where flux is detected above the nebular background, the identification of the flux with thermal emission from the surface of the pulsar is uncertain (see, for example, Tuohy and Garmire 1980). A different approach is the survey of a selected group of known pulsars within a distance of 300 pc. Of the eighteen pulsars observed, six were detected. Although a detailed analysis of these observations is still in progress, a preliminary analysis of data on PSR1055-52 indicates a luminosity in soft X-rays $\approx 4 \times 10^{33}$ erg s^{-1}, corresponding to ~ 0.1 of its rotational energy loss rate. The data is consistent with a blackbody of temperature $\sim 1 \times 10^6$ K.

Further progress in determining the surface temperatures of pulsars would give us information about the formation of neutron stars, ongoing processes at their surfaces and in their interiors, and the equation of state of neutron star matter. Thus, for example, neutron stars cool much more quickly if they contain condensed pions or quark matter.

The most promising observational approach here is soft X-ray imaging of additional nearby pulsars with high sensitivity and sufficient time resolution to test for pulsations.

12. <u>What are the physical processes responsible for converting rotational energy into X-rays and gamma-rays?</u> -- A variety of theoretical models predict the conversion of rotational energy to photons with energies up to and including gamma-rays (Elitzur 1979; Hardee 1979; Harding, Tademaru, and Esposito 1978; Ayasli and Ogelman 1980; Arons 1981; Cheng 1981; Ruderman 1981; for reviews, see Ruderman 1980; Michel 1982). Although longer period pulsars may be unable to produce a dense pair plasma above their polar caps, so that a larger fraction of their luminosity escapes as X- and gamma-rays, shorter period pulsars tend to have a much larger total luminosity. Thus, on balance short period pulsars are favored as X- and gamma-ray emitters. This conclusion is consistent with the fact that so far only the Crab and Vela pulsars are confirmed sources of X- and gamma-radiation (see Manchester and Taylor 1977; Bennett et al. 1977; Swanenberg et al. 1981). The reported detection of PSR1818-04 and PSR1747-46 above 35 MeV by SAS-2 (Ogelman et al. 1976) was not confirmed by COS-B (Mayer-Hasselwander et al. 1980), while Knight et al. (1982) using HEAO-1 were unable to confirm the detection of PSR1822-09 in hard X-rays reported by Mandrou, Vedrenne, and Masnou (1980). For a recent review of gamma-ray observations, see Buccheri (1981).

Answers to this question would shed important light on the magnetic field of the neutron star, the electrodynamics of the pulsar and the surrounding medium, the geometry of the emission region, and the properties of the emitting particles.

Broad-band spectroscopic observations of known nearby pulsars with greatly increased sensitivity at X-ray and hard X-ray energies appear the most likely to assist in answering this question. Of particular importance would be the discovery of one or more very nearby neutron stars with magnetic fields that are too weak or rotation periods that are too long to produce a dense pair plasma. According to some models, such stars would be expected to be "radio quiet," but might still emit an observable flux of hard X-rays or gamma-rays.

d) X-Ray Burst Sources

13. Are they binary systems? -- The X-ray burst sources are widely believed to be binaries (see the review by Lewin and Joss 1981), but direct evidence for binary membership has been discovered only recently. The transient X-ray burst sources Cen X-4 and Aql X-1 (Matsuoka et al. 1980; Koyama et al. 1981) have, in quiescence, optical counterparts which exhibit stellar spectra, a circumstance that has been taken as evidence for their binary nature (van Paradijs et al. 1980; Thorstensen, Charles, and Bowyer 1978). More recently, Walter et al. (1981) and White and Swank (1981) have reported the discovery of periodic absorption events in 4U1915-05 (= MXB1916-05) with a period of 50 minutes, which they interpret as the binary period of this system. This may be the first direct evidence for the binary nature of burst sources.

It is important to confirm the binary character of these sources and to determine their orbital parameters, both because their origin is at present still uncertain and because it is difficult to develop convincing models of their optical and X-ray emission without this information.

The most promising approach is likely to be further searches for evidence of X-ray variation with binary phase. Further optical and X-ray studies of burst sources in nearby galaxies would also make a valuable contribution.

14. To what extent does the thermonuclear flash model agree quantitatively with burst observations? -- Simple thermonuclear flash models (Joss 1978; Joss and Li 1980; Fujimoto, Hanawa, and Miyaji 1981) give reasonable qualitative agreement with the observed properties of so-called type I bursts, but a number of disturbing discrepancies remain (for reviews, see Lewin and Joss 1981; Lewin 1982). Thus, for example, more detailed calculations (Taam and Picklum 1979; Taam 1980, 1981, 1982; Ayasli and Joss 1982) give a wider variety of burst time scales and temperatures than have usually been associated with "standard" type I bursts. Some characteristic properties of burst profiles, such as the double-peaked bursts observed from some sources, have not yet been accounted for. Perhaps a more serious difficulty for current models is the observation of bursts separated by as little as 5-10 minutes (see Hayakawa 1981 and references therein). Such short intervals seem difficult to explain unless the nuclear fuel is burned incompletely (Lamb and Lamb 1978), contrary to the results of most current models.

The peak burst luminosities and temperatures given by current models (Taam 1982; Ayasli and Joss 1982), which assume blackbody emission, are significantly lower than those observed (see Fig. 9). In one calculation, Taam (1982) finds that the photosphere expands to a radius of at least 50 km, producing a very soft burst. Peak luminosities reportedly agree better with observation if the star is assumed to have a magnetic field of $\sim 3 \times 10^{12}$ G, which reduces the opacity of the surface material, but such models conflict with the idea that strongly magnetic stars don't burst. It is interesting to note, however, that most models of the Rapid Burster assume this star has an appreciable magnetic field in order to produce the rapidly repetitive type II bursts, yet the Rapid Burster also produces normal-looking type I bursts. Furthermore, strong magnetic fields are taken to be essential in most gamma-ray burst models. This raises the question of why the neutron stars that produce X-ray and gamma-ray bursts should have different magnetic fields.

Some of these discrepancies may be resolved when models are developed which include factors, such as realistic initial temperature and composition profiles, propagation of detonation or deflagration fronts through the nuclear fuel, hydrodynamic motions, expansion of the photosphere and mass loss, and radiative transfer through the atmosphere and infalling matter, that are known to be important for at least some bursts.

A promising observational approach may be to study, at X-ray and hard X-ray energies, a much wider class of fast transients than the "standard" type I bursts.

15. How are individual burst sources to be interpreted? -- Still more challenging than acounting for the properties of the type I burst sources as a class is to account for the properties of an individual burst source. Among the quantities to be determined are the surface magnetic field, the thermal history of the star, and the history and current value of the mass accretion rate. So far no theoretical calculations have followed a succession of bursts. Given that time scales $\sim 10^2$-10^3 years are required for the cores of flashing neutron stars to reach a quasi-stationary thermal state (Lamb and Lamb 1978), while time scales much longer than the duration of single burst are required for the envelope to reach such a state, bursting neutron stars may always be evolving thermally.

Long-term monitoring of burst activity and inactivity, and accurate measurements of burst and persiste t luminosities, may help to resolve these issues.

16. What is the gating mechanism for the Rapid Burster? -- The magnetospheric and thermal instability model, which assumes radial inflow, gives qualitative agreement with the behavior of the Rapid Burster (Lamb et al. 1977), but raises many questions (for a brief review of Rapid Burster models, see Lewin and Joss 1981). Indirect evidence for disk accretion in other bursters casts doubt on the assumption of approximately radial inflow made in this model, although the Rapid Burster clearly has unique properties. Perhaps a more serious difficulty for this model is the observation by Hakucho of flat-topped type II bursts lasting as long as 10 minutes with intervals between bursts c. at least 20-30 minutes (see Fig. 10; Hayakawa 1981; Oda 1982; and references therein). Such large intervals between bursts would require a very large binary separation in radial flow models. More theoretical work is needed on those instabilities of accretion disks which may have the required very long time scales.

Another puzzle is the relatively small influence which the type I bursts, which are believed to be due to thermonuclear flashes, have on the type II bursts, which are believed to be due to instability in the accretion flow. The small size of the effect (see Fig. 11) favors models involving disk accretion, since disk flows are less affected by radiation from the surface of the star. It is interesting to note that most models of the Rapid Burster invoke an appreciable magnetic field, whereas models of type I bursters usually neglect magnetic fields (see below).

Optical and X-ray observations to constrain the parameters of the system, assuming that it is a binary, or to determine the mode of mass transfer, would be particularly important. One promising approach is X-ray timing and broad-band spectroscopic studies of the interaction between type I and type II bursts.

e) Gamma-Ray Burst Sources

17. What are they? -- An array of Earth-orbiting and interplanetary spacecraft have now provided confirmed positions of six gamma-ray bursts with arcminute accuracy (see Hurley 1982). Many other bursts have yielded positions which are either unconfirmed or less accurate than this. Although radio, X-ray, and optical candidates have been found in the error boxes, no clear association between gamma-ray bursts and other forms of emission has emerged. The event of 1979 March 5 was unique; its identification with the supernova remnant N49 in the Large Magellanic Cloud remains controversial (see Cline 1982). Arcminute positions will continue to be accumulated by multiple spacecraft timing during the next few years, but given the sizable number of positions of this accuracy already available, one cannot expect a major breakthrough in determining the nature of these sources.

Despite the absence of unambiguous identifications with known astrophysical objects, a consensus view that the bursts come from strongly magnetic neutron stars has emerged. The developments that have led to this consensus have recently been summarized by Lamb (1982). They include the properties of the 1979 March 5 event which, though unique, has had a major impact on thinking about gamma-ray bursts in general; theoretical arguments which suggest the presence of a magnetic field of $\sim 10^{12}$ G (Colgate and Petschek 1981); and the reports by Mazets and his colleagues of spectral features (see the review by Teegarden 1982).

The gamma-ray burst sources are one of the few major discoveries of the last decade whose natures remain a puzzle. Confirmation that they are strongly magnetic neutron stars would clear the way for a further advance in our understanding of them.

Arcminute positions based on multiple spacecraft timing may produce an identification, but it is clear that still smaller error boxes will generally be required. Another possibility is the serendipitous positioning of faint gamma-ray burst sources by sensitive hard X-ray imaging detectors, if the latter are flown for the purpose of studying bright, known X-ray sources.

18. What powers them? -- At present the most promising energy sources are accretion onto neutron stars (see, for example, Lamb, Lamb, and Pines 1973; Colgate and Petschek 1981) or nuclear outbursts on such stars (Woosely and Taam 1976; Woosely and Wallace 1982). It is interesting to contrast the latter models, which discuss strong surface magnetic fields, "pools" of fuel on the star, and propagating burning fronts, with the thermonuclear flash models of X-ray bursts, which do not mention such phenomena (for reviews, see Lamb 1982; Woosley 1982).

Hard X-ray spectroscopy may be the most promising method of addressing this question.

19. What is the origin of the continuum emission? -- The expression that has generally been used to characterize the continuum spectra of gamma-ray bursts (see Teegarden 1982) corresponds to the spectrum of optically-thin thermal bremsstrahlung, if the energy dependence of the Gaunt factor, relativistic corrections, and magnetic field effects are ignored. These are, however, substantial effects for the energies and magnetic field strengths of interest. Few attempts to fit an actual bremsstrahlung emission spectrum to the observations have been reported to date. Actually, for the source to be optically-thin would require an aspect ratio $\gtrsim 10^3:1$ (Bussard and Lamb 1982; Lamb 1982). Such a ratio could arise if the bursts are produced by thin sheets or filaments of plasma, but it is hard to see why such a distribution should always occur, as would be necessary to account for the apparent universality of the spectral shape.

Another possibility is that the bursts are made up of a sequence of brief flickers, each shorter than the 4s detector accumulation time, which emit Comptonized thermal spectra with falling temperatures. The average count-rate spectrum of such a source is quite similar to that of optically-thin bremsstrahlung, as pointed out by Bussard and Lamb (1982).

This issue can only be resolved by hard X-ray and gamma-ray spectroscopy with better spectral and temporal resolution.

20. What are the origins of observed spectral features? -- Reported spectral features are generally of two types: extinction in the energy range 10-50 keV, and excess emission in the energy range 300-650 keV (again see Teegarden 1982). The lower energy features could be due to cyclotron scattering, if the magnetic field in the source varies by at least a factor of two (Bussard and Lamb 1982), or a time-varying low energy cutoff (Lamb 1982). The extinction cannot be due to photoelectric absorption by iron or nickel unless the magnetic field is $\gtrsim 2 \times 10^{13}$ G.

The higher energy features are widely interpreted as redshifted electron-positron annihilation radiation. However, the shapes of these features are poorly determined at present, and hence their interpretation remains in doubt. If the lower energy features are due to cyclotron scattering, more accurate determinations of the 300-650 keV emission features could provide a cross-check on the inferred magnetic field strength, since magnetic broadening and one-photon annihilation become important for fields $\gtrsim 10^{13}$ G (see Fig. 12).

Again, the only observations with real promise of resolving these issues are hard X-ray and gamma-ray spectroscopic studies with better spectral and temporal resolution.

III. DEVELOPMENTS DURING THE NEXT DECADE

Table 1 lists the various types of observations that have been cited above as promising means to answer the questions that have been posed, together with approved or proposed missions that are capable of making the type of observation in question during the next decade. This accounting suggests that the most discovery space is available to an instrument capable of carrying out hard X-ray imaging and spectroscopy. There is also a need for

X-ray and soft X-ray observations with an instrument which has arcminute angular resolution and an effective area substantially larger than that of ROSAT or EXOSAT.

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TABLE 1

APPROVED OR PROPOSED MISSIONS

Suggested Observation	Missions[1]
Soft X-ray imaging	ROSAT, EXOSAT
Soft X-ray spectroscopy	ROSAT, EXOSAT
X-ray timing	XTE, EXOSAT, ASTRO-C
X-ray (2-60 keV) spectroscopy	XTE, EXOSAT, ASTRO-B
X-ray sky monitoring	XTE, ASTRO-B, ASTRO-C
Iron-line spectroscopy	(XTE, EXOSAT, ASTRO-B)
Hard X-ray imaging	------
Hard X-ray spectroscopy	------
Studies of nearby galaxies	ST, (AXAF)
Gamma-ray spectroscopy	GRO

[1]Missions whose primary objectives are other than the suggested observations listed here are shown in parenthesis.

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FIGURE CAPTIONS

Fig. 1. Data from nine pulsing X-ray sources plotted against theoretical spin-up curves for disk accretion (from Ghosh, Lamb, and Zylstra 1982). Here P and $\dot{P}$ are the pulse period and period derivative, respectively, and L is the accretion luminosity. Each curve is labeled with the assumed stellar magnetic moment in units of 10^{30} G cm^3.

Fig. 2. The variation of the pulse period of Vela X-1 (from Hayakawa 1981). The straight line represents a constant spin-down rate $\dot{P}/P = -1.5 \times 10^{-4}$ yr^{-1}.

Fig. 3. Two examples of luminosity variations and the resulting pulse frequency behavior, illustrating the effects of different magnetic moments and luminosity patterns (from Elsner, Ghosh, and Lamb 1980). Also shown is the observed behavior of A0535+26.

Fig. 4. Pulse waveforms of Vela X-1 observed at different energies (see Rappaport and Joss 1981).

Fig. 5. Deconvoluted Her X-1 spectrum from the 1976 MPI/AIT balloon observation (from Trümper et al. 1978).

Fig. 6. Left and right panels show pulse shapes obtained by convolving model beam shapes with the rotation of the neutron star for two different sets of inclination angles (from Mészáros and Bonazzola 1981).

Fig. 7. Theoretical power transfer functions for a two-component neutron star model (left) and a generalized two-component model with a finite-frequency internal mode (right). The power transfer function describes the amplitude of pulse frequency fluctuations excited by an internal or external fluctuating torque of fixed strength (from Lamb 1981b).

Fig. 8. Theoretical cooling curves compared with observations (from Van Riper and Lamb 1981). The results for each star are shown as regions bounded by the cooling curves for zero magnetic field and B = 4.4×10^{12} G. Dark shading: soft equation of state; medium shading: stiff equation of state; light shading: star with a pion condensate; no shading: star with free quarks. Also shown are detections (dots) and upper limits (arrows) obtained from EINSTEIN soft X-ray observations of pulsars and supernova remanants. The cross-hatched rectangle characterizes the upper limits that have been obtained for 7 nearby pulsars.

Fig. 9. Variation of the surface luminosity with time for a burst produced by a combined hydrogen-helium shell flash (from Taam 1982). The effective temperature is given at the peak of the burst, and after one e-folding time.

Fig. 10. Time profiles of a typical trapezoidal burst from the Rapid Burster as seen in two different energy channels (from Hayakawa 1981).

Fig. 11. Bursts from the Rapid Burster (from Lewin and Joss 1981). The type I bursts (marked as "special") occur independently of the sequence of the rapidly repetitive type II bursts (numbered separately).

Fig. 12. Rate coefficients for nonrelativistic electron-positron annihilation into one or two photons, as a function of magnetic field strength (from Bussard and Lamb 1982).

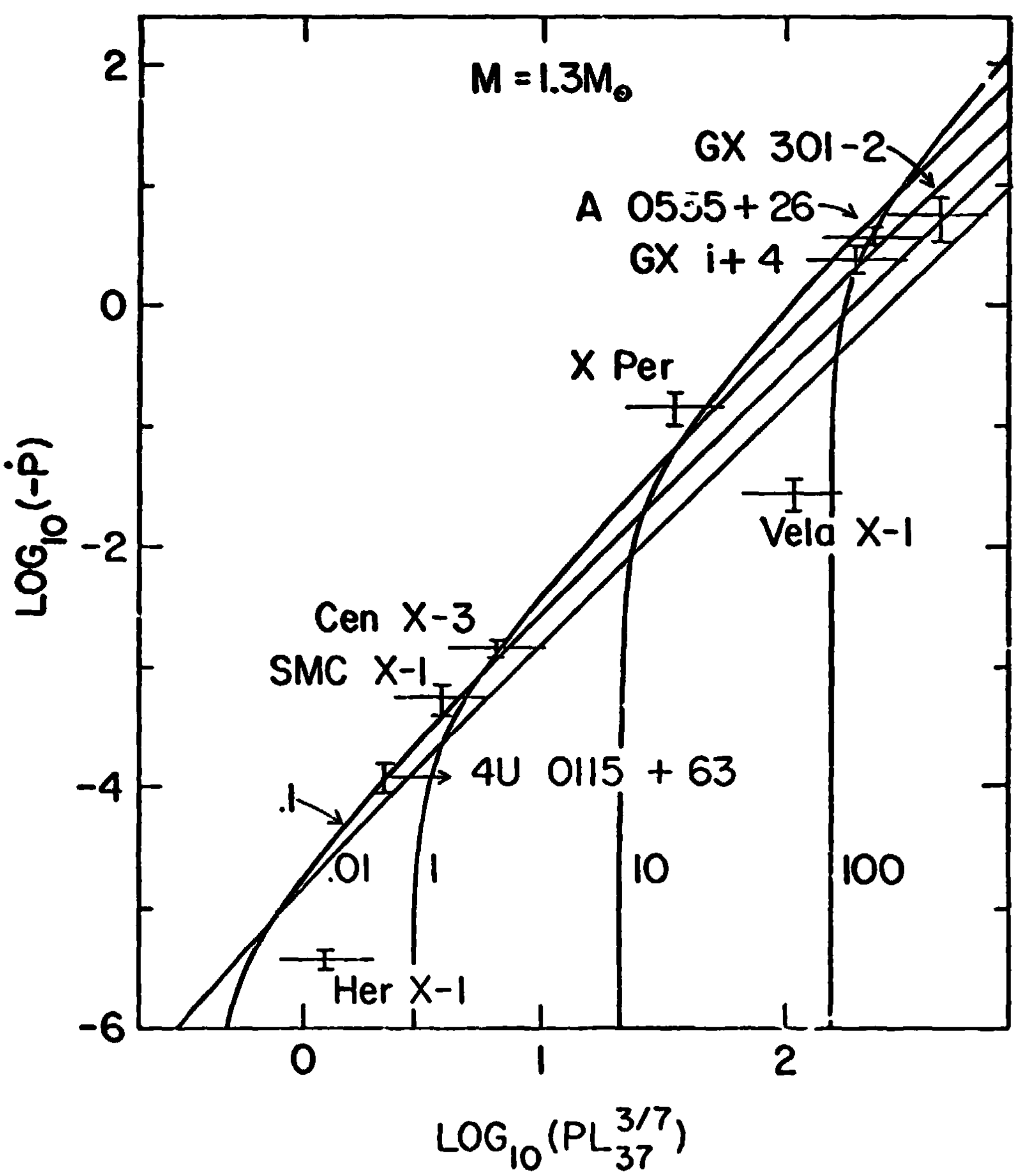

M = 1.3M⊙
GX 301-2
A 0535+26
GX 1+4
X Per
Vela X-1
Cen X-3
SMC X-1
4U 0115 + 63
.1
.01
1
10
100
Her X-1
2
0
-2
-4
-6
0
1
2
LOG10(-Ṗ)
LOG10(PL37 3/7)

Figure 1

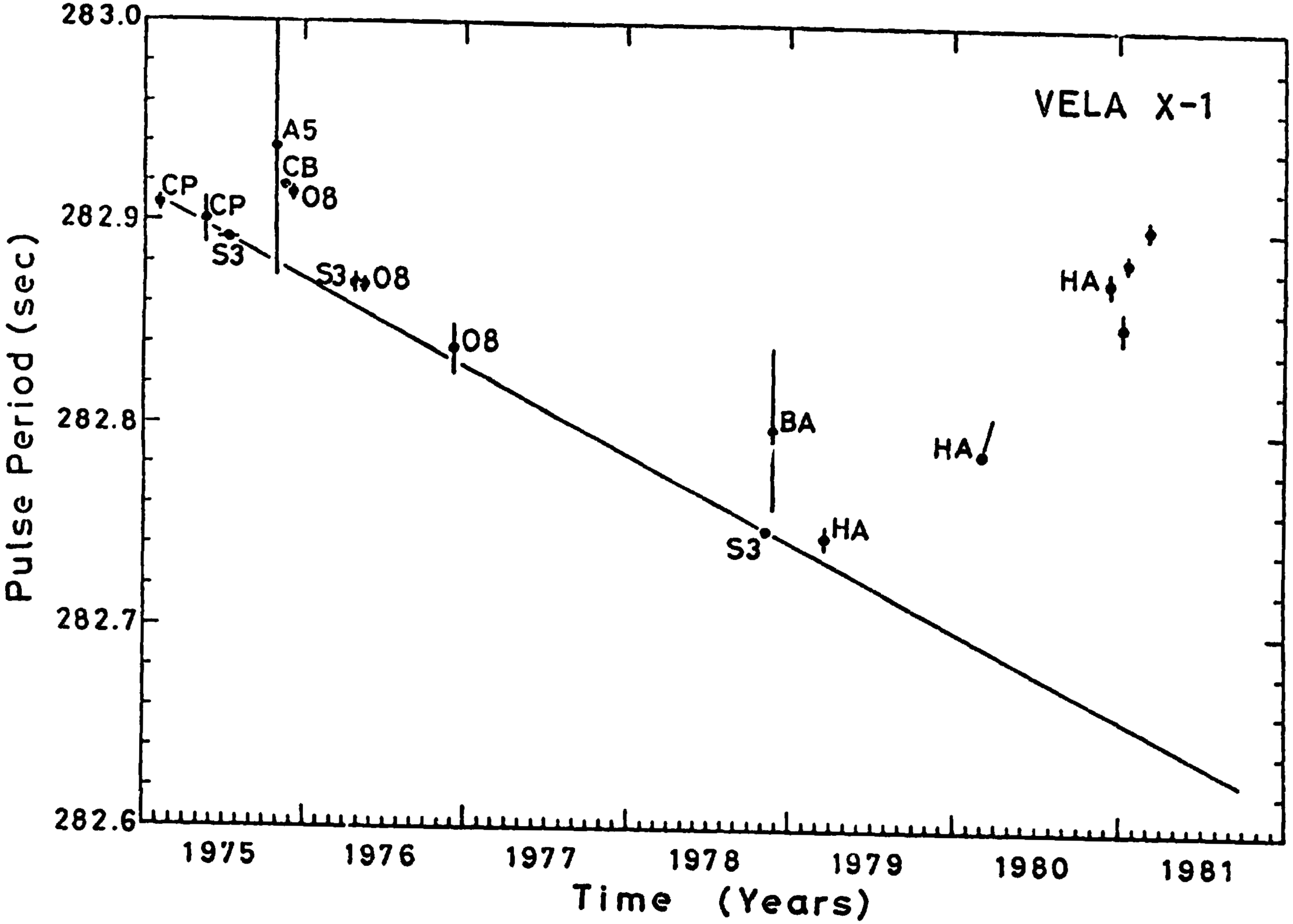

VELA X-1
283.0
282.9
282.8
282.7
282.6
Pulse Period (sec)
1975
1976
1977
1978
1979
1980
1981
Time (Years)
CP
CP
S3
A5
CB
O8
S3
O8
O8
BA
S3
HA
HA
HA

Figure 2

ORIGINAL PAGE IS
OF POOR QUALITY

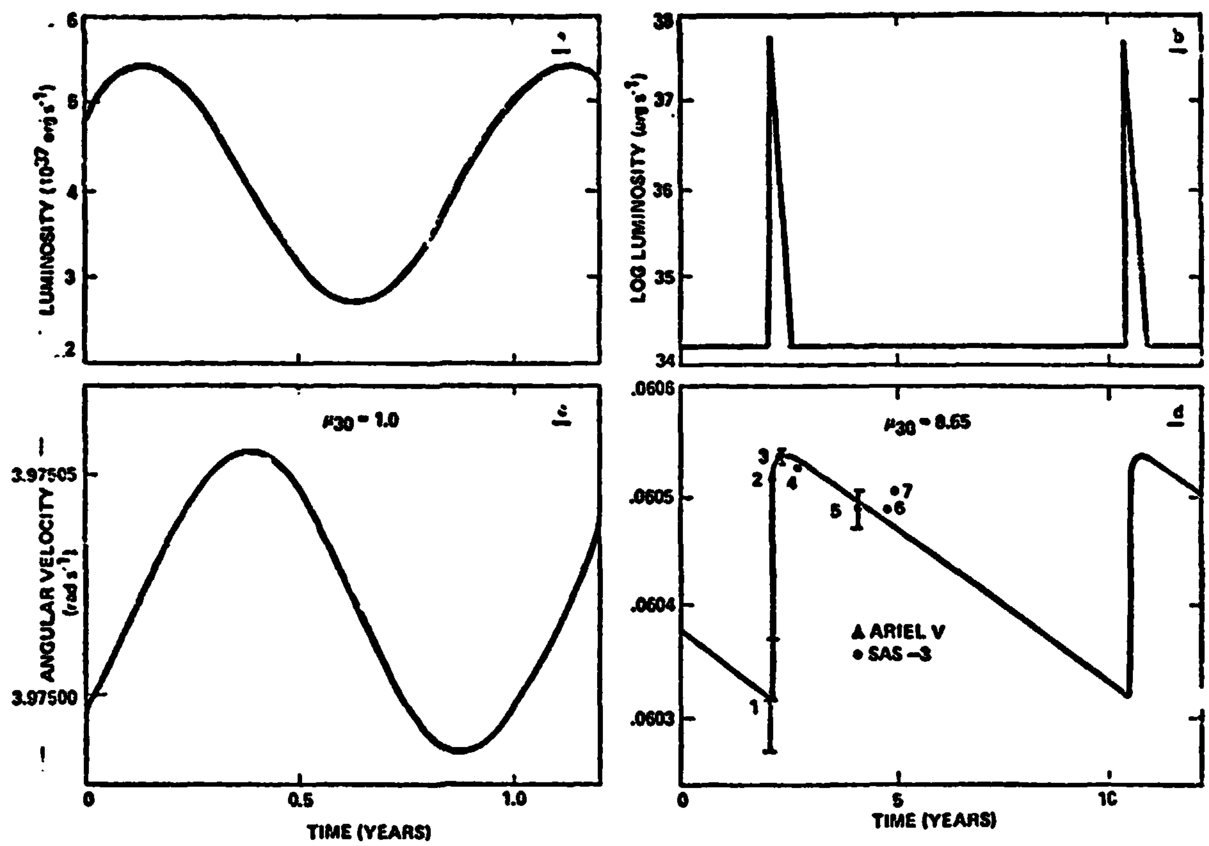


Figure 3

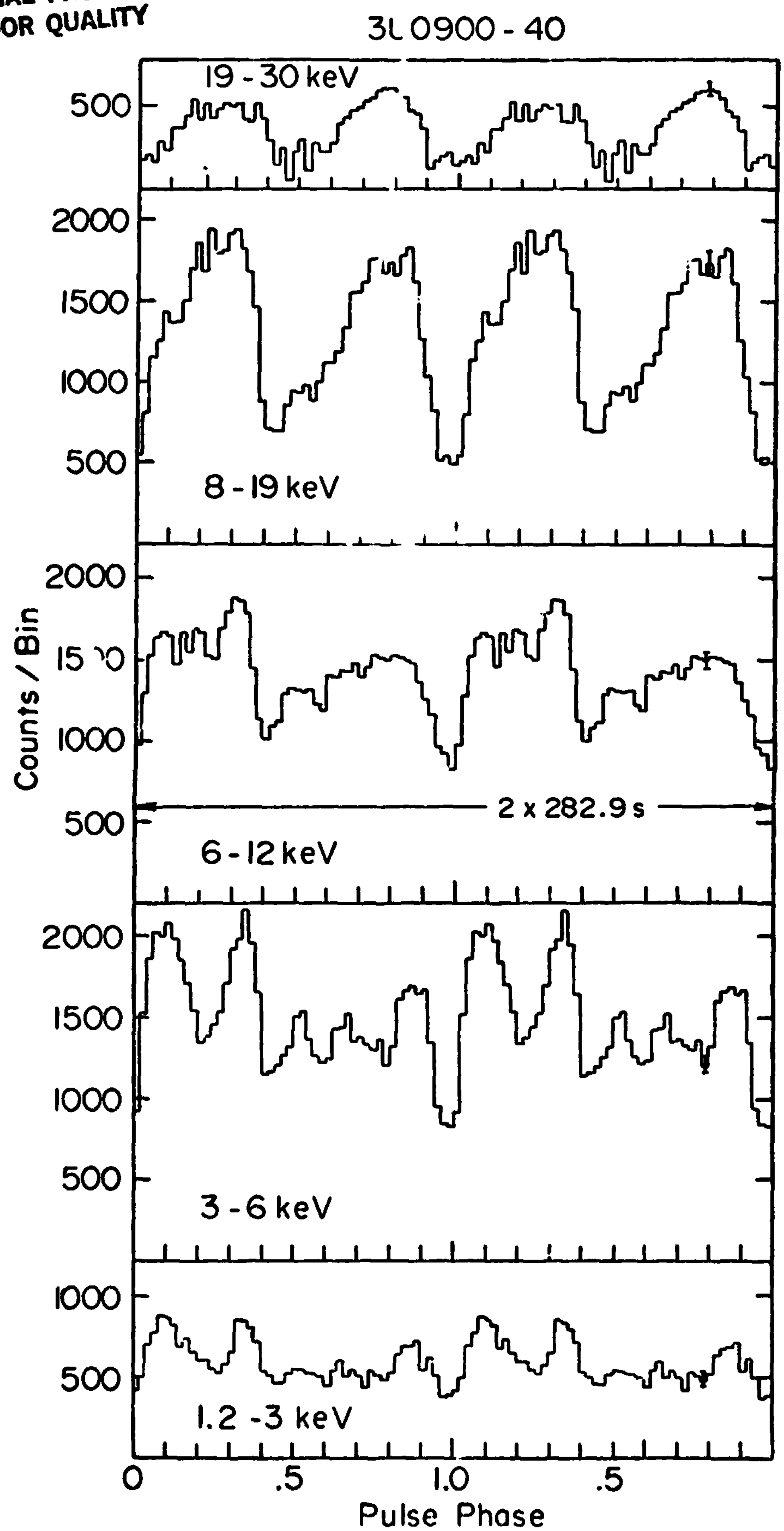

3U 0900-40
19 - 30 keV
500
2000
1500
1000
500
8 - 19 keV
2000
1500
1000
500
2 x 282.9 s
6 - 12 keV
2000
1500
1000
500
3 - 6 keV
1000
500
1.2 - 3 keV
Counts / Bin
0
.5
1.0
.5
Pulse Phase

Figure 4

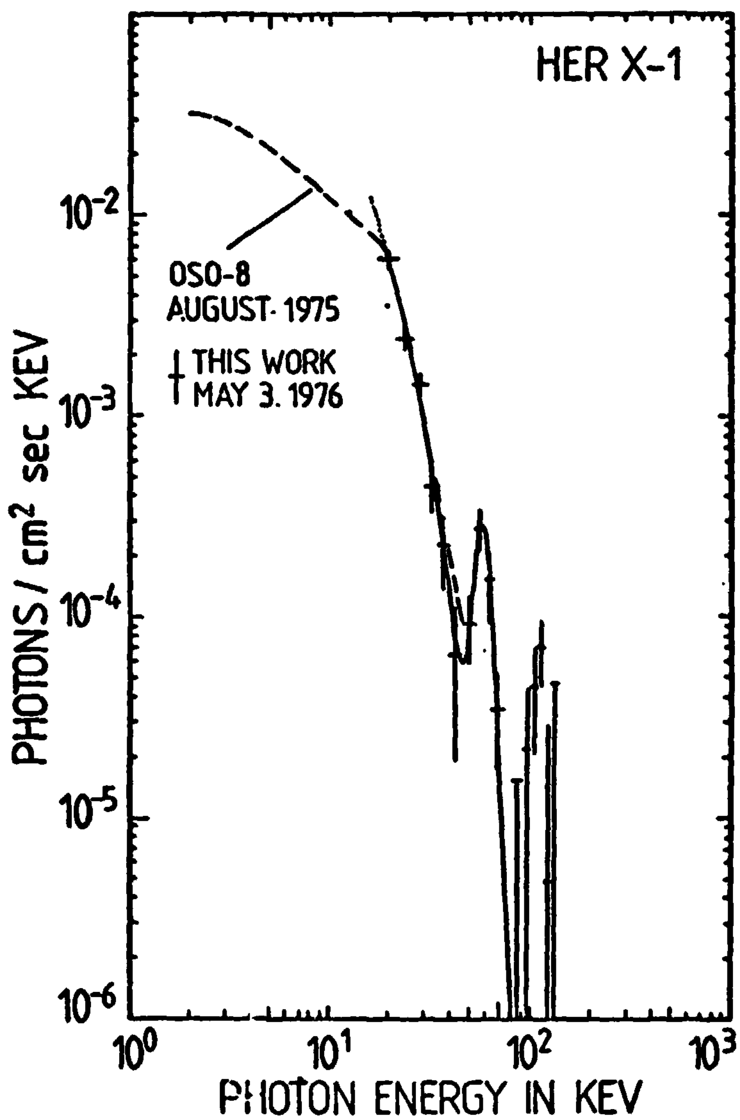
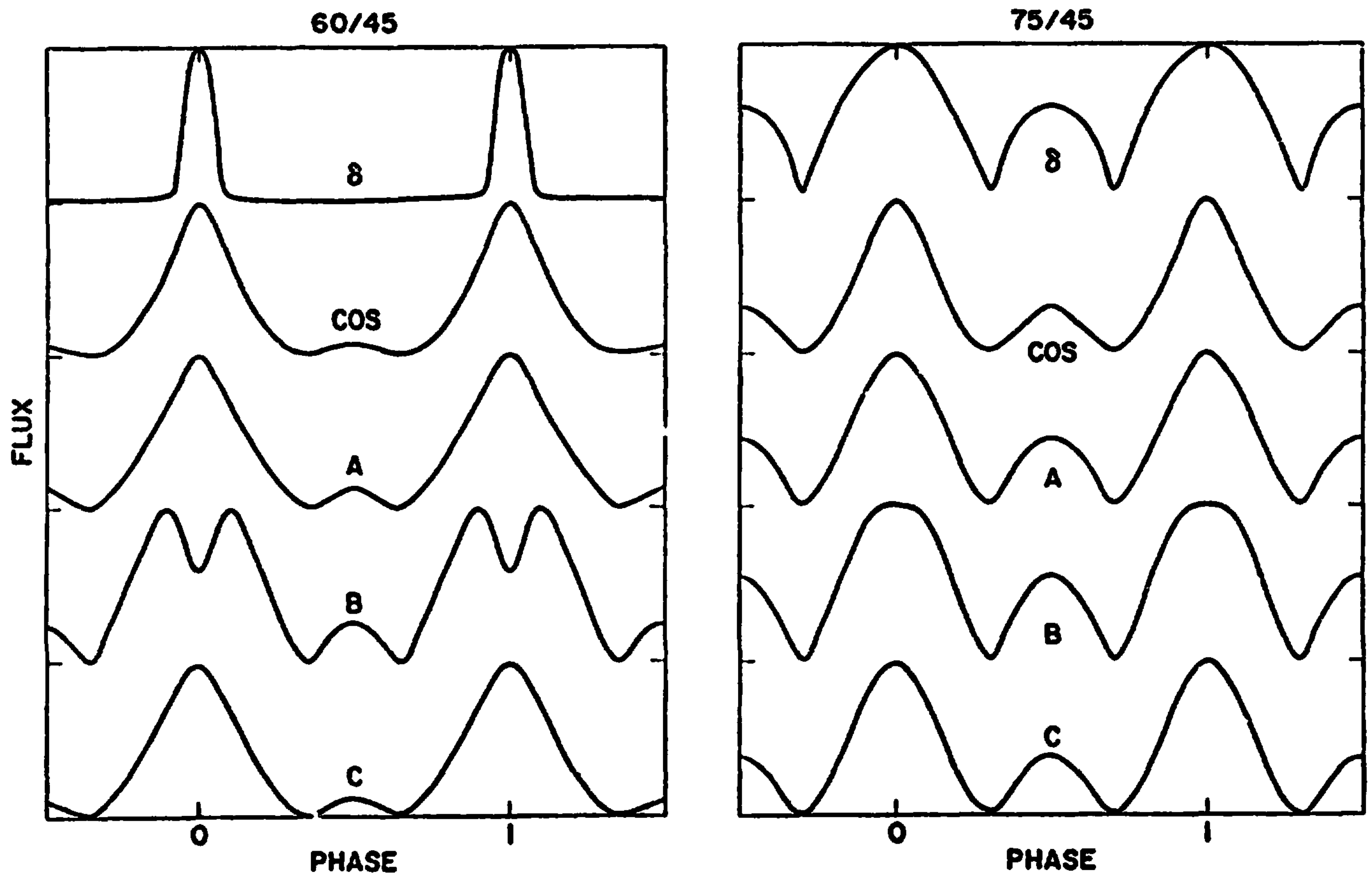

HER X-1
OSO-8
AUGUST 1975
THIS WORK
MAY 3. 1976
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
PHOTONS / cm² sec KEV
10^{0}
10^{1}
10^{2}
10^{3}
PHOTON ENERGY IN KEV

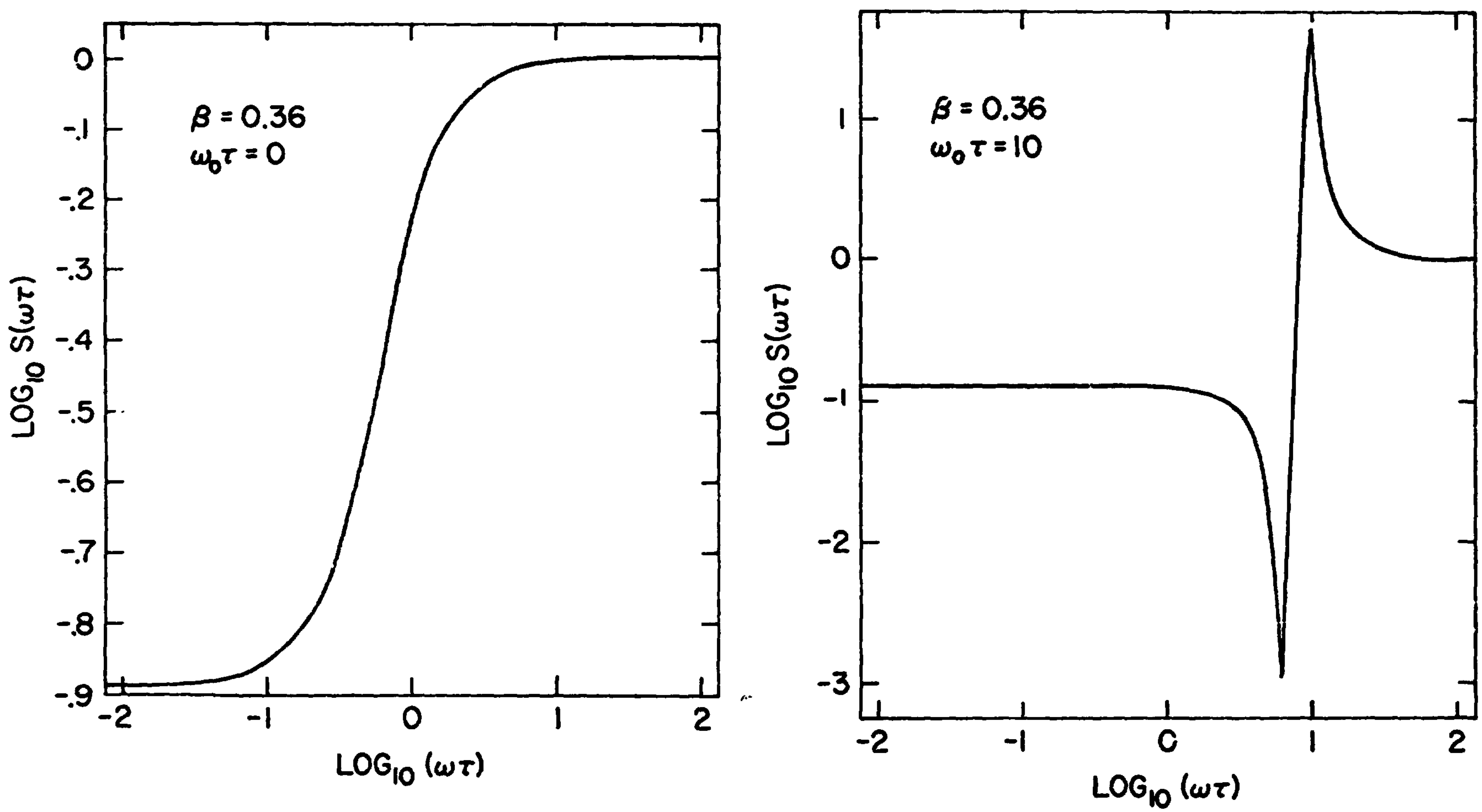
Figure 5



ORIGINAL PAGE IS OF POOR QUALITY

Figure 6

Figure 7


β = 0.36
ω₀τ = 0
LOG₁₀ S(ωτ)
LOG₁₀ (ωτ)
0
-.1
-.2
-.3
-.4
-.5
-.6
-.7
-.8
-.9
-2
-1
0
1
2
β = 0.36
ω₀τ = 10
LOG₁₀ S(ωτ)
LOG₁₀ (ωτ)
1
0
-1
-2
-3
-2
-1
0
1
2

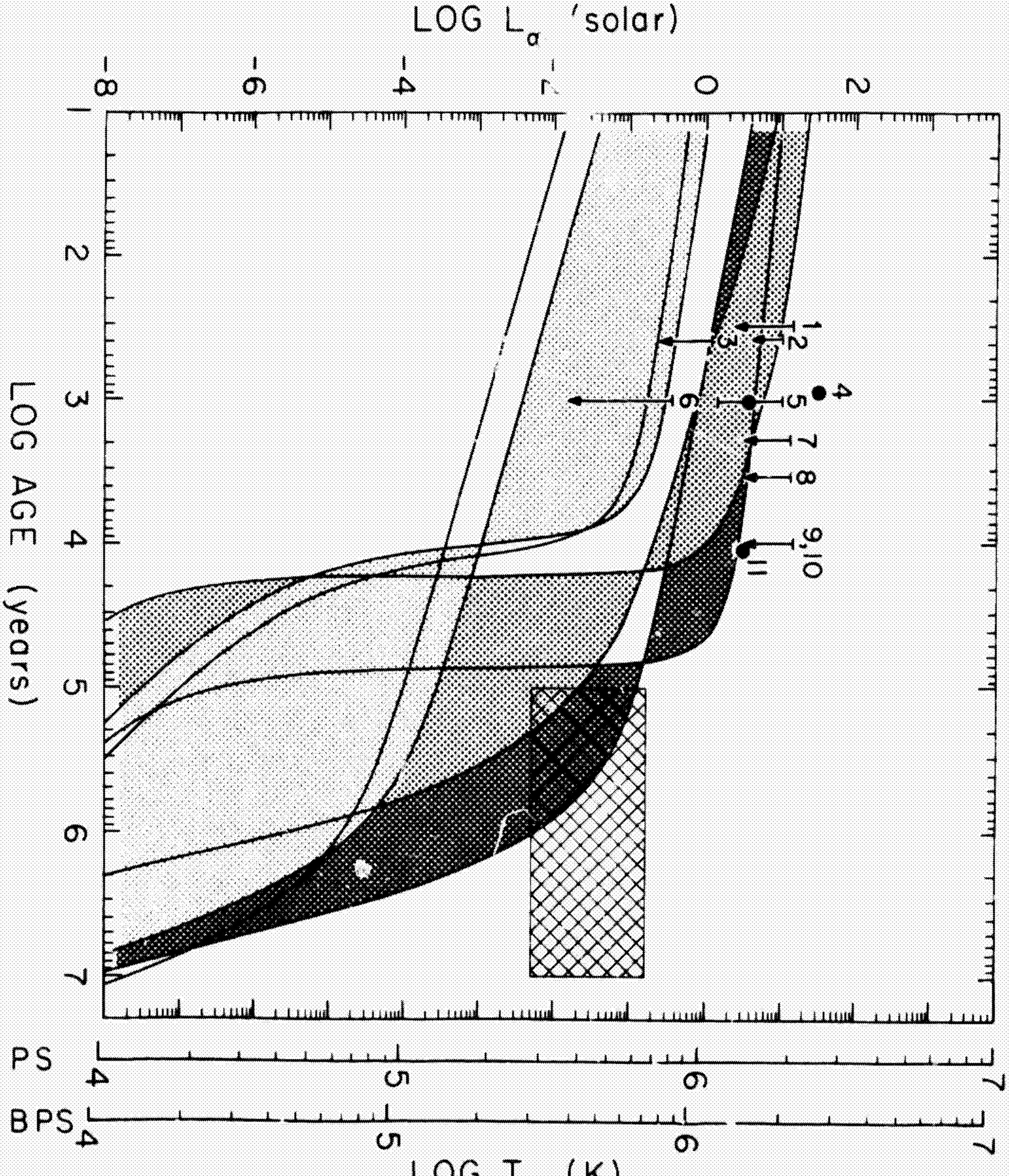


Figure 8

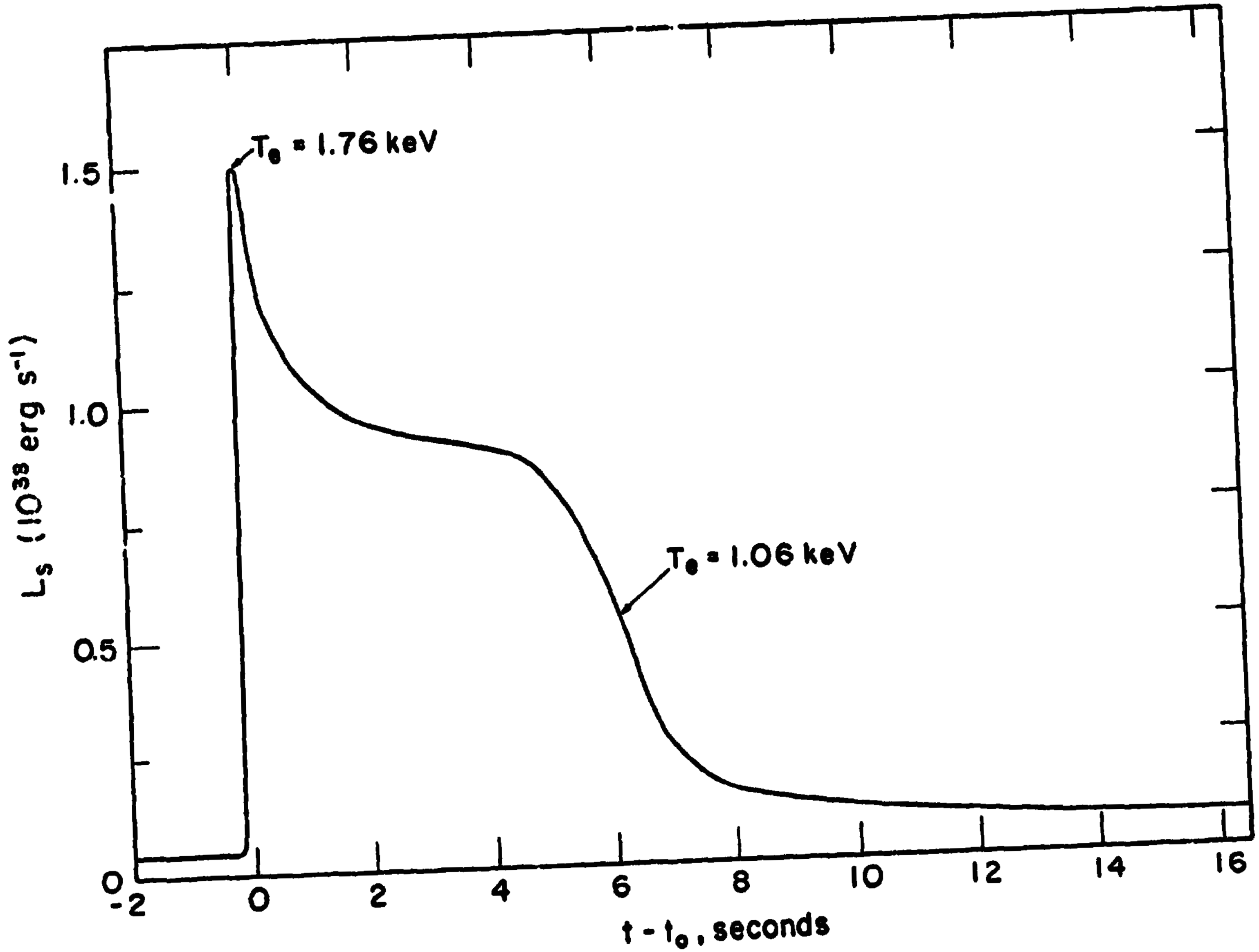

T_e = 1.76 keV
T_e = 1.06 keV
1.5
1.0
0.5
0
L_s (10^{38} erg s^{-1})
-2
0
2
4
6
8
10
12
14
16
$t - t_o$, seconds

Figure 9

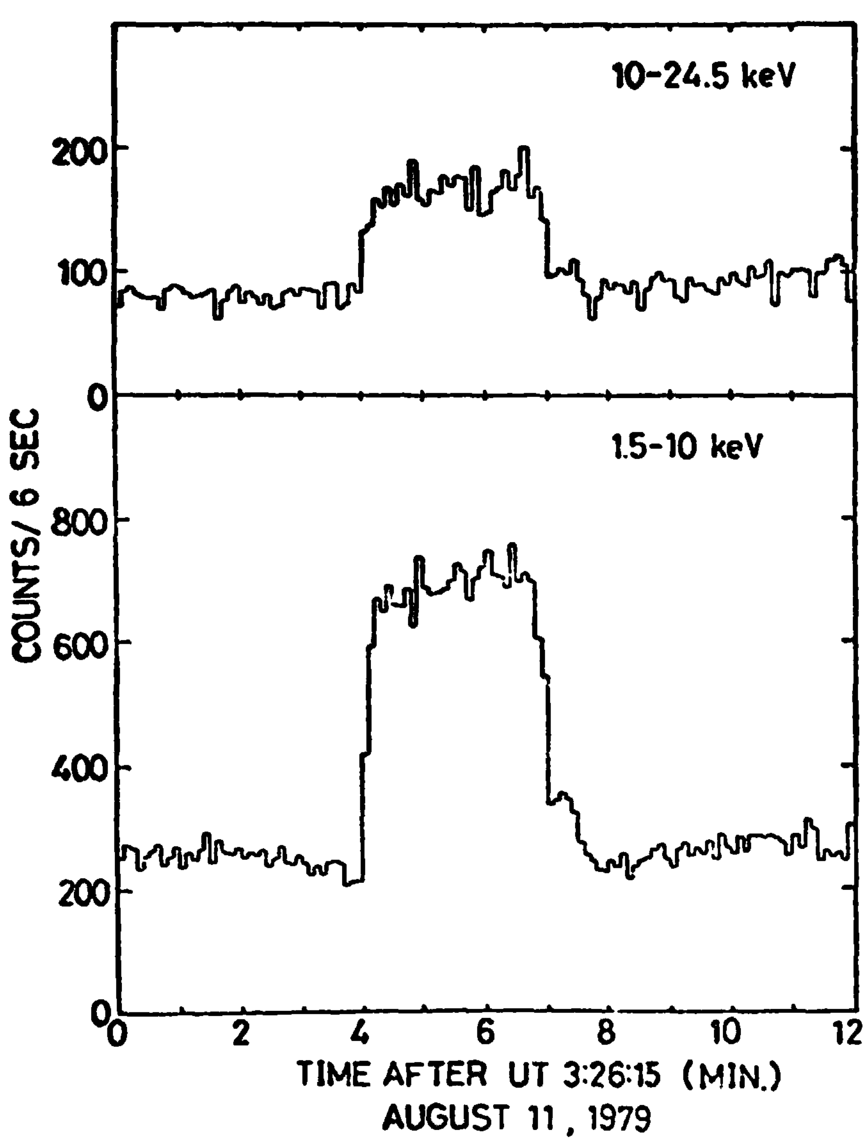

10-24.5 keV
1.5-10 keV
COUNTS/ 6 SEC
0
100
200
0
200
400
600
800
0
2
4
6
8
10
12
TIME AFTER UT 3:26:15 (MIN.)
AUGUST 11, 1979

Figure 10

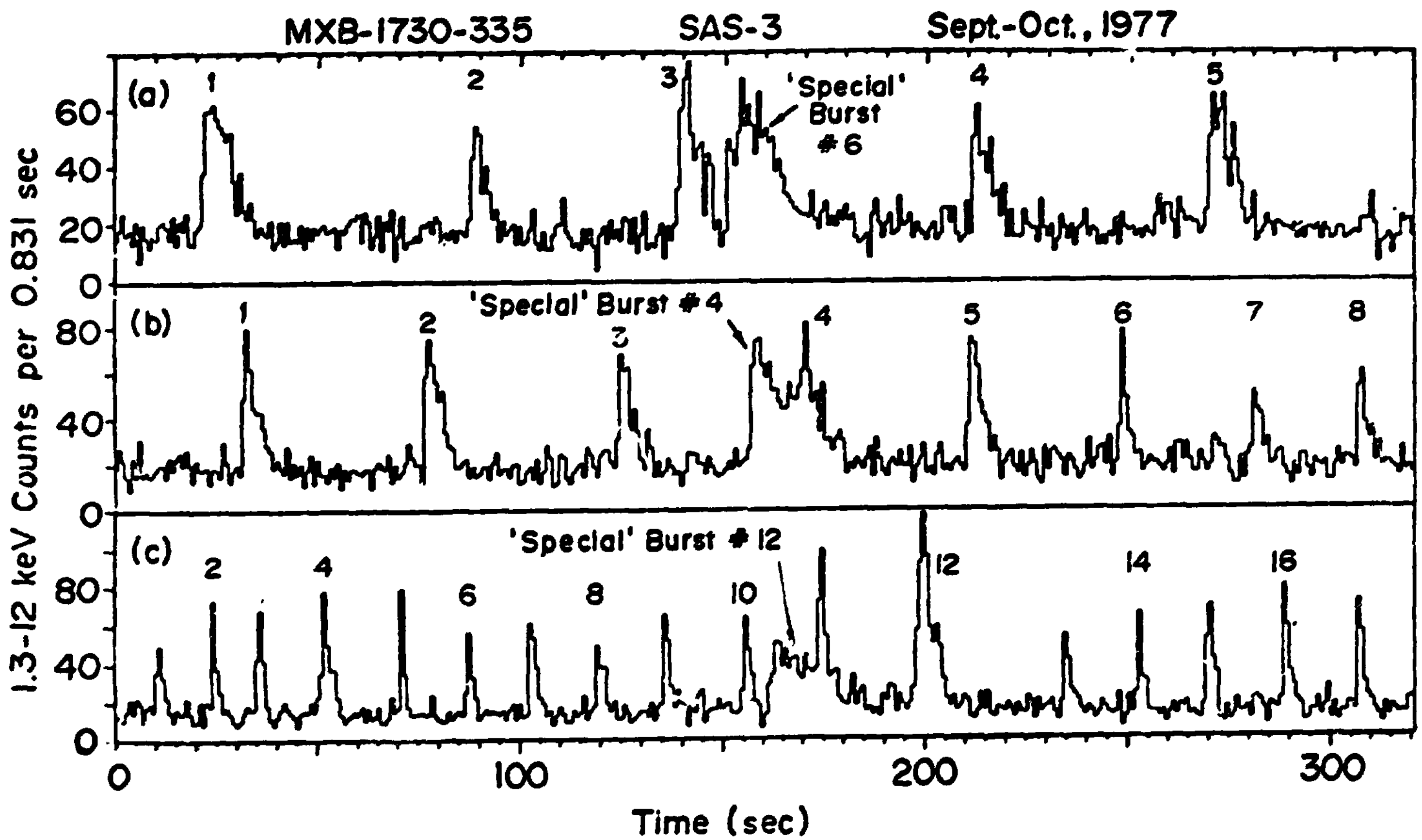

MXB-1730-335
SAS-3
Sept.-Oct., 1977
(a)
'Special' Burst #6
(b)
'Special' Burst #4
(c)
'Special' Burst #12
1.3-12 keV Counts per 0.831 sec
Time (sec)

Figure 11

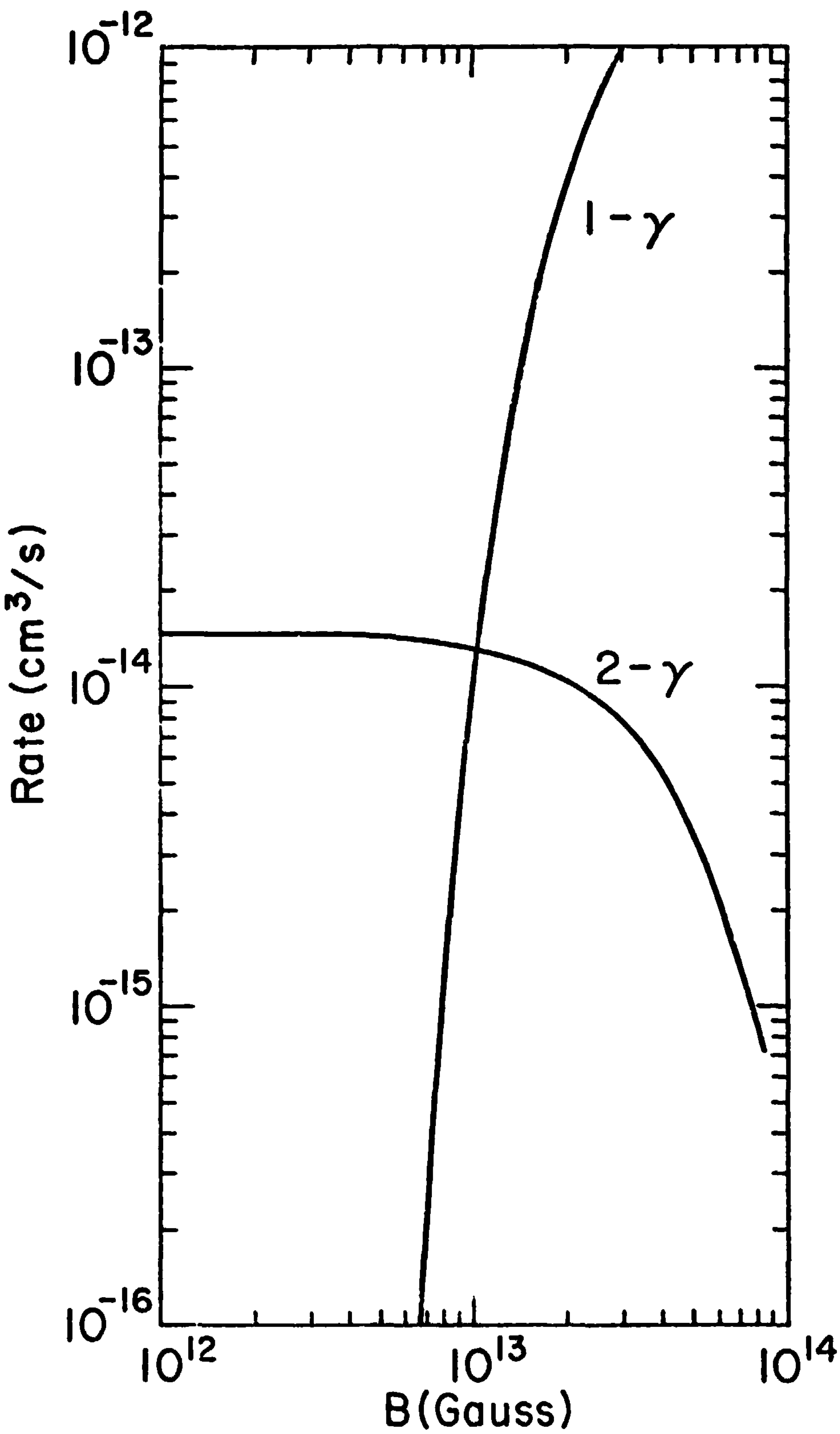

10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
Rate (cm^3/s)
$1-\gamma$
$2-\gamma$
10^{12}
10^{13}
10^{14}
B(Gauss)

Figure 12