BINARY X-RAY STARS AND SUPERNOVAE OF TYPE I

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Abstract. Most of the strong galactic X-ray sources must be low mass, close binary systems, such as Her X-1 and Sco X-1. Two evolutionary scenarios are discussed, both involving type I supernovae that occur when mass-accreting white dwarfs are driven over their mass limit. In one, accepting the correctness of the idea that a neutron star or black hole is the seat of the X-ray emission, the SN occurs before the system is an X-ray source. Another possibility is that the white dwarf is the X-ray source, just prior to its collapse and the ensuing SN.

1. Introduction

During the past four years, a combination of X-ray satellite data and optical observations has revealed that a number of the strong galactic X-ray sources are members of close binary systems. The optically identified X-ray sources are listed in Table I; for most of these objects the binary character is revealed unambiguously through the observation of eclipses, periodic Doppler shifts or periodic intensity variations. In one case (Cyg X-2) a companion star is seen but there is no other evidence of duplicity.

There has developed a standard model for these objects based on these and other data; namely, that the X-ray emission is produced near the surface of a neutron star or a black hole from hot matter which has been accreted from the nearby companion star (cf. Giacconi, 1974; Rees, 1974; Gursky and Schreier, 1975). The model is by no means definitive, but it can account for much of the observational data, at least qualitatively, and is certainly an acceptable working hypothesis. In this paper, I will present the outline of an evolutionary scenario which may be operating for some of these X-ray sources and in which a type I SN occurs.

The SN occurs when a white dwarf is driven over its mass limit by accretion from a companion star, and leaves behind a neutron star or black hole remnant. This means of producing SN type I was first discussed by Schatzman (1963). The scenario is almost forced if one adopts the standard model, since the binary X-ray sources, in combination with their apparent population type requires a prior SN type I. Furthermore, mass accreting white dwarfs are one of the more common elements in the Galaxy. However, as will be discussed in Section 6, a good case can be made for X-ray emission from the white dwarf immediately prior to its undergoing an SN, when close to its mass limit.

There has been much discussion of the evolution of one set of X-ray binaries including Cyg X-1, 2U0900–40, 2U1700–37, Cen X-3 and SMC X-1 (see de Loore and de Grève, 1976, and Van den Heuvel, 1976. This set of binaries is characterized by the presence of an O-B giant or supergiant as the companion star. It is the other X-ray binaries in Table I, namely, Her X-1, Sco X-1, Cyg X-2, and Cyg X-3 with which I am concerned. These systems cannot contain massive stars. In two cases, the companion star is seen. Also, the very short binary periods of Cyg X-3 and Sco X-1 argue for a star of normal size and thus normal mass: in Sco X-1 it is hardly possible to hide a bright O-B star. Furthermore, as will be discussed below, the population type of these X-ray sources is different from that of the massive binaries.

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TABLE I

Characteristics of identified X-ray sources

Name		Binary period	Optical Companion	b	Remarks
3U1956 + 35	Cyg X-1	5.6 days	9 mag O.97 Ib	3°	
1118–60	Cen X-3	2.1 days	13 mag B0Ib-III	0°	4.8-sec X-ray pulse period
0900–40	Vela X-1	8.9 days	6 mag B0.5Ib	+4°	
1700–37		3.4 days	6 mag O7f	2°	
0115–37	SMC X-1	3.9 days	13 mag B0Ib	–	
1617–15	Sco X-1	0.8 days	?	+24°	
1653 + 35	Her X-1	1.7 days	15 mag late A	+38°	Hz-Her. 1.2-sec pulse period
2030 + 40	Cyg X-3	0.2 days	–	+1°	Heavily obscured, seen only $\lambda \geqslant 1\,\mu$
2142 + 38	Cyg X-2	?	14 mag G	–11°	

2. Distributional Properties of the Galactic X-Ray Sources

In presenting the material in this and the next section, I am attempting to show that both the galactic X-ray sources and the SN type I at least originate in a common stellar population. The distribution of the low latitude X-ray sources from the 3U catalog (Giacconi *et al.*, 1974) is shown in Figure 1. The average properties obtained from these and other data have already been summarized (cf. Gursky and Schreier, 1975; Gursky, 1973); however, I want to call attention to a few essential points. For one, the high-mass X-ray binaries, Cyg X-1, 0900–40, 1700–37 and Cen X-3 all lie very close to the galactic plane, as expected for such young objects. Of the remaining sources in Table I, Sco X-1, Her X-1 and Cyg X-2 lie at large angular distances from the plane which is more consistent with the average latitude of all the sources of about 5°. Salpeter (1972) has already made note of this large average latitude and suggested the parent population of the X-ray sources to be an old disc population. There is even evidence for Population II objects in Figure 1, based on the association of at least two of the X-ray sources with globular clusters as first pointed out by Gursky and Schreier (1975). This association has been discussed in more detail recently by Clark *et al.* (1975).

It is clear from Figure 1 that the high mass binaries are only a minority of the galactic X-ray sources; the fact that they comprise half the identified sources attests to the ease with which they can be discovered optically compared to the low mass systems.

The other relevant average properties of these sources are their total number (several hundred in the Galaxy) and luminosity (in the range $10^{36}-10^{38}$ erg s^{-1}).

3. Distributional Properties of Type I Supernovae

As summarized by Tammann (1974) the type I Supernovae display the following characteristics:

(1) They are the only type SN found in elliptical galaxies.

(2) The frequency of type I SN found in spiral galaxies shows a strong dependence on the inclination of the Galaxy indicating an origin in the disc rather than in the halo of the Galaxy.

Along with the spectroscopic data, which show a lack of hydrogen in the ejected matter,

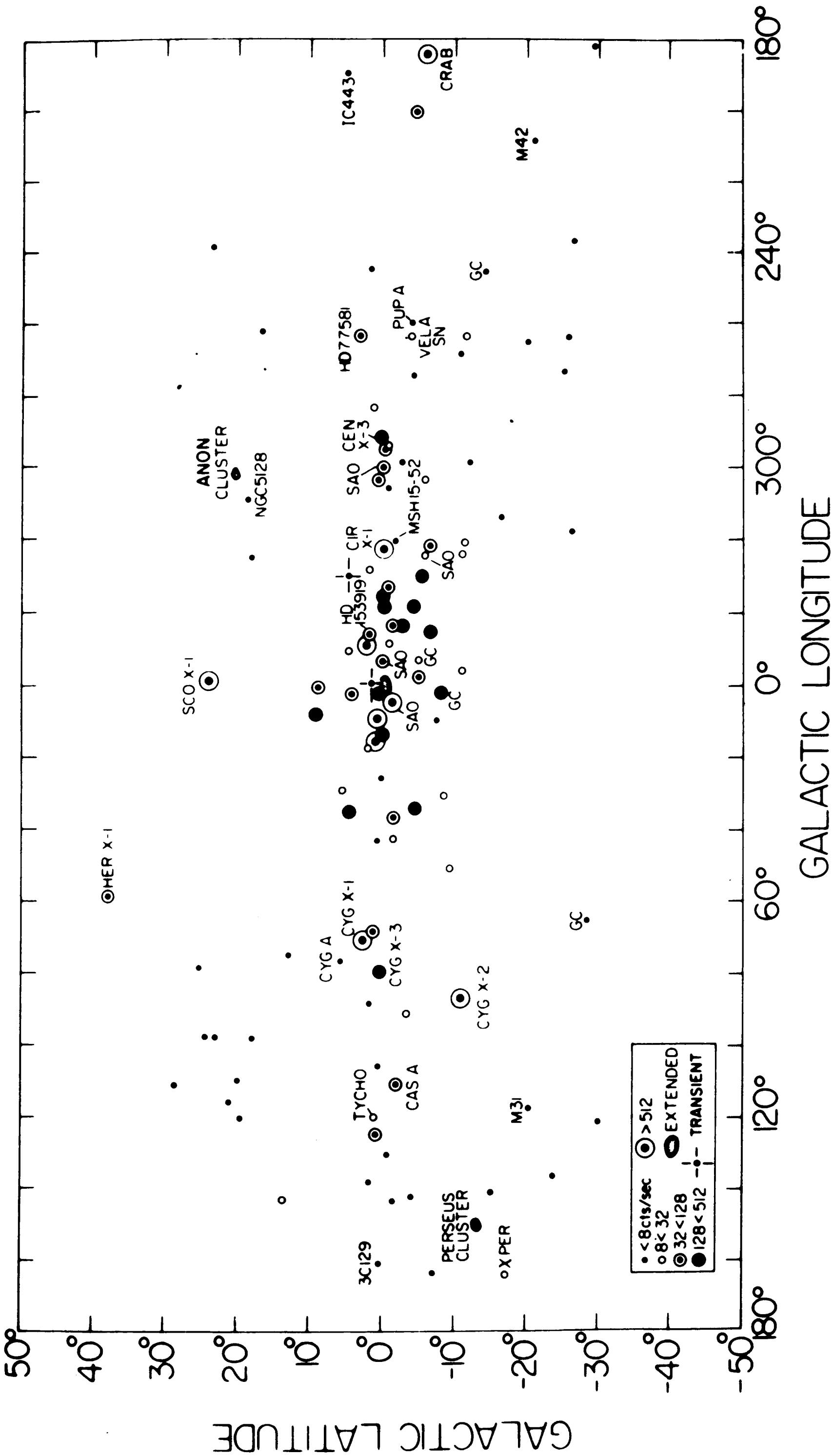

Fig. 1. Galactic distribution of 3U X-ray sources. With the exception of Her X-1, only sources with $l < 30°$ are plotted. GC indicates source coincident with a globular cluster, SAO indicates source coincident with star in SAO catalog. Also, HD77581 = 3U0900−40 and HD153919 = 3U1700−37.

these distributional characteristics imply that the SN type I are likely to originate in Population II objects (in elliptical galaxies) and in an old disc population (in spiral galaxies). Thus, the progenitor populations of type I SN and of galactic X-ray sources may be the same.

This possible overlap between populations of galactic X-ray sources and type I SN is the only observational evidence for a physical association between the two. The only other argument for an association is a theoretical one; namely, it seems impossible to form neutron stars without a supernova explosion. Unfortunately, as yet there are no X-ray equivalents of the Crab and Vela SNR – pulsar associations which directly tie together supernova and pulsars.

4. Evolutionary Scheme for Making X-Ray Sources

Whelan and Iben (1973) described an evolutionary scenario for making type I SN in elliptical galaxies beginning with a star of mass between $1.3–3\,M_{\odot}$ with a $0.8\,M_{\odot}$ companion and a separation of $\sim 600\,R_{\odot}$. With time, the higher mass star will evolve to a white dwarf with mass close to the Chandrasekhar limit and the radius is chosen to avoid significant mass transfer to the companion. After $\sim 10^{10}$ yr of the $0.8\,M_{\odot}$ will begin its red giant phase, dump matter onto its white dwarf companion which now may find itself above its stable mass limit and either explode or collapse producing the type I SN. If a neutron star remains following the SN, further accretion from the companion will result in an X-ray source. Also, as will be discussed below, the system may also be an X-ray source immediately prior to the SN explosion.

This specific scenario cannot account for any of the identified low mass X-ray sources since the orbital period is much too great, but it could be operative for certain of the unidentified sources, particularly those found in globular clusters. However, as noted, the large separation was invoked to avoid mass transfer to the $0.8\,M_{\odot}$ star and allow an SN after 10^{10} yr. For the galactic X-ray sources which reside in the disc, so severe a constraint on the age does not apply and the orbital radius can be made much smaller. Essentially, any close binary system in which one member is seen to be a white dwarf could be the progenitor of a type I SN and subsequently of a low mass X-ray binary. The immediate progenitor of the type I SN in which matter is being transferred to the white dwarf is likely to be a cataclysmic variable. Evolutionary schemes leading to cataclysmic variables and type I SN have been discussed by Warner (1974).

5. Discussion – X-Ray Sources Following the SN Type I

I can summarize the discussion presented here as follows:

(1) There exists a class of low mass X-ray binaries which appear to contain neutron stars thus requiring an earlier SN.

(2) This class of objects appears to be of the same population type as the SN type I.

(3) It has been argued that a type I SN results from a mass accreting white dwarf.

The conclusion is that one can adopt, at least as a working hypothesis, that the X-ray binaries were preceded by a type I SN which occurred in a white dwarf in a binary system.

There are substantial theoretical problems with this view which must be mentioned. First, there is the number of predicted X-ray sources. The rate of SN type I is estimated to be 0.01 yr^{-1}. The lifetime of the X-ray sources will be determined by the duration of the mass transfer stage which itself must be related to the mass transfer rate and cannot exceed about $10^{-8}\ M_\odot\ yr^{-1}$ without running up against the Eddington limiting luminosity. In the limit therefore if every type I SN leads to an X-ray source we would predict $\sim 10^6$ X-ray sources in the Galaxy which is high by at least 10^3 compared to the observed number. At the present state of knowledge, this is not necessarily a problem; rather, it implies that only a small fraction of the SN type I result in X-ray sources. Also the lifetime estimate above for the X-ray sources may be seriously in error. One other question is simply whether accretion onto a white dwarf will really increase its mass. The answer is not obviously positive since the energy released by burning the accreted hydrogen exceeds by about a factor 50 the gravitational binding energy of that hydrogen; furthermore, the novae models of Starrfield *et al.* (1974) allow that almost all the accreted mass is ejected during the novae outburst.

Granted that the Chandrasekhar mass limit is real, and a white dwarf finding itself above that mass will collapse, will the collapse result in a neutron star or will the star simply explode, i.e., undergo nuclear reactions which release more energy than the net binding energy of the star? Schatzman (1974) has described the competition between collapse dominated by beta decay which would lead to neutron star formation and collapse dominated by nuclear reactions leading to stellar disruption. Also, Wheeler (1974) has described the collapse of a carbon core white dwarf and its implications for type I SN. One can only reiterate the comment by Whelan and Iben (1973) emphasizing the importance of further theoretical investigation of the evolution of white dwarfs during mass accretion and of the physical process occurring during collapse.

With respect to these problems, however, one is helped by the numbers; namely, only a small fraction of the SN type I need to be followed by an X-ray source phase.

6. Discussion – X-Ray Sources Prior to the SN Type I

It is worthwhile to review the standard model for the low mass binaries on which the above scheme depends. There seems little doubt that a compact star at least as small as a white dwarf is the seat of the X-ray emission for the following reasons.

(1) Mass accretion appears to be the energy source since we see close binary stars in which there is evidence of mass transfer as the X-ray sources.

(2) All the X-ray sources exhibit significant time variability on short scales (minutes at the least).

(3) In no case is more than a single star observed.

By themselves these observations argue for an object as small as a white dwarf, at least, to be the X-ray source. Furthermore, the energetics also argue for stars at least this compact. To obtain the required X-ray luminosity by accretion requires mass transfer rates of 10^{-5}–$10^{-7}\ M_\odot\ yr^{-1}$ if a white dwarf is the compact star and correspondingly less if it is a neutron star or black hole. The mass transfer requirements become prohibitive if a normal size star is the seat of the X-ray emission.

However, these arguments by themselves cannot exclude the white dwarf hypothesis. Why then do we believe the neutron star or black hole hypothesis? There are, in fact, good reasons. One of the X-ray sources in the category, Her X-1, is almost certainly a neutron star. Its X-ray emission pulses with a 1.24-sec period which can be understood as originating in mass accreting rotating, magnetized neutron star (cf. Lamb *et al.*, 1973). The case cannot be made so directly for the others; rather one is left with indirect arguments as follows.

(1) Hydrogen burning is about 50 times more efficient than accretion in producing energy in a white dwarf. Furthermore, the hydrogen is expected to burn well below the surface and release its energy via black body emission at the surface in the temperature range 10^5-10^6 K, well below what is seen in the X-ray sources (10^7-10^8 K, black body equivalent). The significance of this is that there should be substantial luminosity in excess of the X-ray emission in these sources. Even if this could be hidden by interstellar absorption, it could hardly be present in those sources which already seem to be radiating at or near the Eddington limit between 1–10 keV. Blumenthal *et al.* (1972) and Cameron (1975) have suggested that instabilities or vibrations could transport energy from a hydrogen shell to the surface where it appears as hard X-rays; however, Katz and Salpeter (1974) have shown this to be an inefficient process.

(2) The disk model of accretion as presented by Pringle and Rees (1972) and by Shakura and Sunyaev (1973) yields too low temperatures to radiate the observed X-rays when a white dwarf is the central object (Shakura, 1972).

(3) Not one of the known binary systems containing a mass accreting white dwarf is seen to be a strong X-ray source. The recent discovery of SS Cyg as an X-ray source (Rappaport *et al.*, 1974) is not an exception since its emission is confined below 1 keV and may occur only during the flare stage.

Thus the arguments against a white dwarf hypothesis are either theoretical or by exclusion. Furthermore, these arguments lose their force under a particularly interesting circumstance. It is a well known property of white dwarfs that as they increase in mass their size decreases, and close to the mass limit they may have a radius of only 10^3 km instead of the canonical 10^4 km (cf. Schatzman, 1958). In this case, many of the theoretical arguments cited above against the white dwarf hypothesis lose their force. In particular, the luminosity due to accretion is comparable to that of hydrogen burning, lower accretion rates are required and higher surface temperatures can be accommodated. Furthermore, such systems may be rare and short-lived accounting for the small number of X-ray sources. Thus, we come to the remarkable possibility that a white dwarf system either just before or some time after undergoing a SN explosion is a good candidate for the strong galactic X-ray sources.

Unless we get extraordinary observational luck, in a way that is hard to foresee, the hypotheses presented can only be resolved by theoretical work; particularly the questions of the ultimate fate of mass accreting white dwarfs and the conditions for the generation and emergence of X-rays from white dwarfs and smaller objects. Otherwise we may simply satisfy ourselves with the prospects that in the distant future, after the observation of hundreds of SN in our galaxy, the answer may emerge.

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