J. Astron. Space Sci., Vol. 5, No. 2, 1988

〈解說〉

Introduction to Properties of Galactic X-ray Sources

Chul-Sung Choi
Institute of Space Science and Astronomy, Taejon 302-348
Kyoung W. Min
Korea Institute of Technology, Taejon 302-338
Tu-Hwan Kim
Institute of Space Science and Astronomy, Taejon 302-348
(Received November 5, 1988; Accepted November 26, 1988)

Abstract

Since the successful observation by Uhuru, the first astronomical satellite, X-ray astronomy has become one of the rapidly developing fields in astronomy. The scientific results provide us the unique opportunity to understand the high energy nature of X-ray sources. We now know that our galaxy contains many different types of X-ray sources such as the compact X-ray sources, galactic bulge sources in addition to the Sun, the brightest X-ray source in the sky. In this study we review the general properties of galactic X-ray sources, the characteristics of periodic compact X-ray sources, and bursters as well as the models.

I. Introduction

We can say that the goal of astronomy is to determine the physical property of the Universe and its components. To carry out this purpose, astronomers had been fulfilled their curiosity through the optical and radio observations. However, we may have fragmentary knowledge about the nature of universe if we rely on these ground-based observations only, since the permitted frequency band of electromagnetic radiation of the earth's atmosphere is a small fraction compared with its full scope of frequency. We need space observations using rockets, balloons, or satellites in order to observe X-ray, gamma-ray, and EUV(extreme ultraviolet) ranges of the electromagnetic radiation.

X-rays and gamma-rays are energetic enough to reach the solar system through the interstellar medium even from the other side of our galaxy. These X-rays and gamma-rays are roughly divided according to the energy or the wave length as displayed in Figure 1.

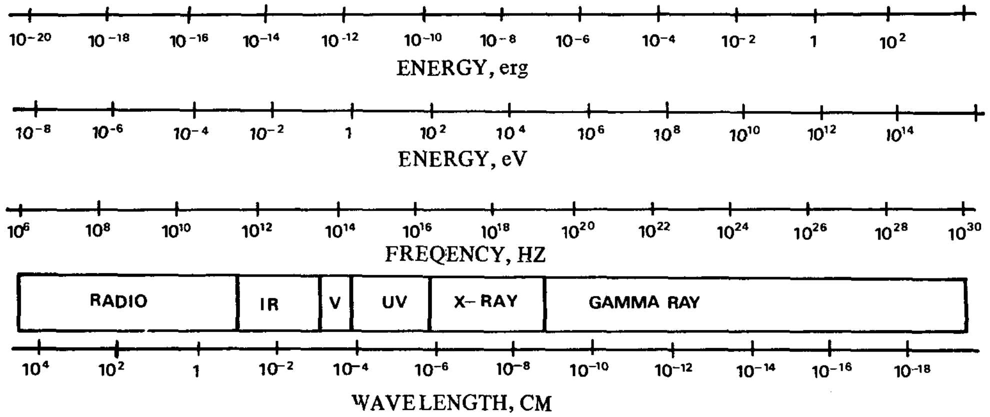

Fig. 1. The electromagnetic spectrum.

X-ray astronomy is a branch of space astronomy which carries out scientific research above the atmosphere. Space astronomy had its beginnings on the top of a V-2 rocket on October 10, 1946 when NRL(Naval Research Laboratory) group obtained the first spectra of the sun in the ultraviolet beyond the atmospheric cutoff. In 1948, Burnight used an Aerobee rocket carrying photographic films covered by thin metal plates to detect solar X-rays(Giacconi and Gursky 1974). Since then, X-ray astronomy is one of the most rapidly developing fields due to the parallel advances in launch and detection capability.

On 12 June 1962, MIT and ASE(American Science and Engineering) team launched a rocket and discovered the first non-solar X-ray Source(Sco X-1). Sco X-1 is one of the brightest celestial X-ray sources and the total photon flux of it is about 100 photons $cm^{-2} s^{-1}$.

The first X-ray astronomy satellite, Uhuru, opened a new era in this field. The satellite was launched on 12 December 1970 and scientific payload was designed to conduct an all-sky survey in X-rays in the 2-20 KeV energy band to a limiting intensity of about 10^{-4} Sco X-1(Giacconi and Gursky 1974). It was the first of NASA's small astronomy satellite(SAS). Following the Uhuru, many satellites were launched to observe celestial X-ray sources as shown in Table 1. Some of the important events in X-ray astronomy are also summarized in Figure 2.

In the present paper we will discuss the features and models of galactic X-ray sources. The general characteristics are presented in section II. In section III, optical counterparts and pulse profiles of binary X-ray sources are discussed. Section IV describes various physical models and properties of galactic bulge sources and bursters.

Table 1. X-ray astronomical satellites

Name	Nation	Launching year
SAS-1(Uhuru)	USA	1970
OSO-7	USA	1971
OAO-C(Copernicus)	USA	1972
ANS	Netherlands	1974
Ariel-5	England	1975
SAS-3	USA	1975
HEAO-1	USA	1977
HEAO-2(Einstein)	USA	1978
Hakucho	Japan	1979
Ariel-6	England	1979
Astro-A(Hinotori)	Japan	1981
Astro-B(Tenma)	Japan	1983
EXOSAT	ESA*	1983
Astro-C(Ginga)	Japan	1987

* ESA: European Space Agency.

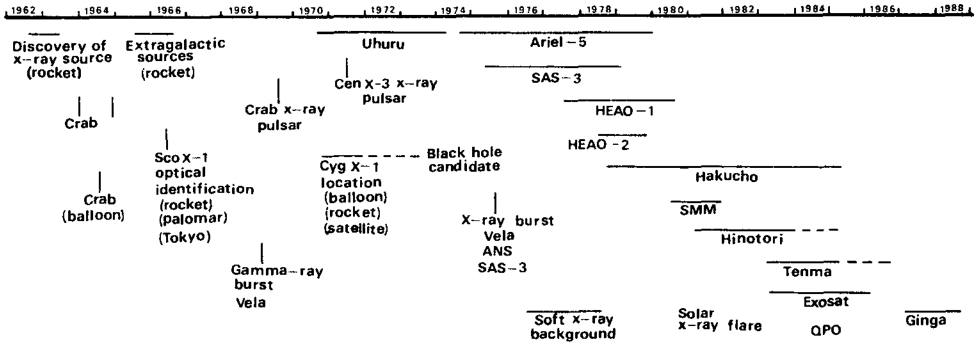

Fig. 2. Chronology of the X-ray astronomy(Oda 1987).

II. General characteristics of the galactic X-ray sources

The galactic X-ray sources can be classified into two groups except the Sun according to their essential properties such as compact X-ray sources and GBXs(galactic bulge X-ray sources).

Most of compact X-ray sources are regarded as binary systems which are formed of visible stars and compact objects such as white dwarfs, neutron stars, and black holes. The binary X-ray sources that contain compact objects can be divided into two groups in turn according to the optical components: the massive systems($M \gtrsim 10M_{\odot}$)and the low-mass systems ($M \leqslant 2\ M_{\odot}$). The massive systems(type I) have late O or early B type stars which are massive and luminous. Such young, population I systems are associated with spiral arms and star forming regions. Examples of type I X-ray sources with massive companions include Cyg X-1(3U 1956+35), Cen X-3 (3U 1118-60), 4U 0900-40, 4U 1538-52, and GX 301-2 etc. Another system(type II) is associated with stars with low-mass and later spectral type. Such stars are similar to the Sun in luminosity and temperature. Examples of type II sources with low-mass companions include Cyg X-2(3U 2142+38), Cyg X-3(3U 2030+40), Her X-1(4U 1653+35), Sco X-1(3U 1617-15), and Aql X-1 (1M 1908+005) etc.

According to van den Heuvel(1983), the numbers of massive and low-mass X-ray system in the Galaxy are roughly the same. This implies that the fraction of X-ray binaries formed per unit time among massive stars is about 10^5-10^7 times larger than among low-mass stars because the expected life time of low-mass system is about 10^3-10^4 times longer than that of massive systems and the formation rate of low-mass stars is about 10^2-10^3 times larger than that of massive ones.

The GBXs show some characteristics unlike the binary X-ray sources as follows(Lewin and Joss 1983).

- No X-ray eclipses have been found.
- As a burst faded, the ratio of soft to hard X-rays steadily increased in most of the GBXs. From this spectral softening, we know that the burst source was cooling.
- The ratio of their X-ray to optical luminosities, Lx/Lopt, ranges from $\sim 10^2$ to $\sim 10^4$. For the massive X-ray binary systems this ratio ranges $\sim 10^{-3}$ to $\sim 10^1$.

According to Bradt and McClintock(1983), X-ray sources have been found in 12 globular clusters.

The distribution of galactic X-ray sources in 4U catalog is displayed in galactic coordinate in Figure 3(Forman et al. 1978). Also, X-ray source catalogs are presented in Table 2. From Figure 3., we know the followings(Gursky and Schreier 1975). The general feature of the galactic sources shows a strong concentration of sources at low galactic latitude. The sources at high galactic latitude are much weaker and many of them can be identified as specific extragalactic objects. The exceptions are Her X-1 and Sco X-1 which are identified as galactic objects. Typically, the galactic X-ray sources lie at distances ranging from 500 pc to 10 kpc and have luminosities of $10^{35}-10^{38}$ erg s^{-1}.

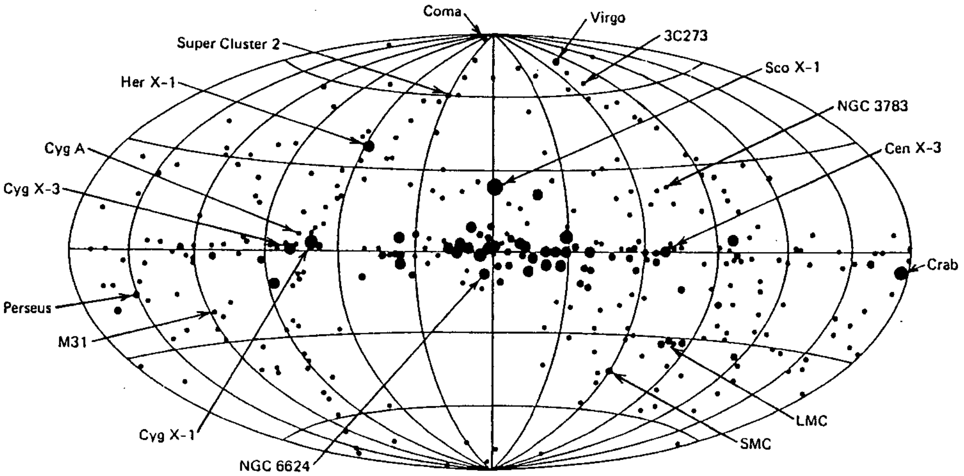

Fig. 3. X-ray sources of 4U catalog are displayed in the galactic coordinate system. The size of the symbols representing the source is proportional to the logarithm of the peak source intensity(Forman et al. 1978).

Table 2. X-ray source catalogs obtained from the observation by several astronomical satellites

	Name	Reference
The UHURU Catalog	2U	Giacconi et al.(1972).
	3U	Giacconi et al.(1974).
	4U	Forman et al.(1978).
Ariel – V Catalog	2A	Cooke et al.(1978).
	3A	Warwick et al.(1981).
	3A	Mchardy et al.(1981).
HEAO – 1 Catalog	A – 1	Wood et al.(1984).
	A – 2	Marshall et al.(1979).
	A – 2	Nugent et al.(1983).
	A – 4	Levine et al.(1984)
OSO – 7		Markert et al.(1979)
SAS – 3	1S	Bradt et al.(1977)

III. Binary X-ray Sources(Compact X-ray Sources)

Zeldovich and Guseynov(1966) suggested that the motion of the gas in the gravitational field of a collapsed star, whose existence was predicted by general relativity, can give X-rays. The observation of X-rays from single-line spectroscopic binaries gives a strong evidence of the existence of either a black hole or a neutron star.

According to Gursky and Schreier(1975), the collapsed star is believed to be a neutron star or a black hole on the basis of following reasons.

- Many of the sources are positively confirmed as being in binary systems because a large fraction of compact X-ray sources are observed in close binary systems.
- The short time variability of the X-ray emission requires a compact emission region.
- Mass accretion onto a neutron star or a black hole from its nearby companion should be an extremely efficient means of generating X-rays.

The X-ray emission of binary systems is thought to be generated by the mass transfer from the visible star onto the collapsed companion. For a mass accretion rate of $\dot{M}$, the total gravitational potential energy released per second is given by(Blumenthal and Tucker 1974)

$$L \sim GM_c\dot{M}/R \simeq 1.2 \times 10^{33}(M_c/M_\odot)(R_\odot/R)(\dot{M}/10^{-8} M_\odot y_r{}^{-1}) \text{ erg s}^{-1}, \quad \cdots\cdots (1)$$

where M_c is the mass of collapsed object. The identified X-ray sources have luminosities from 10^{35} to 10^{38} erg s^{-1}. If we use the equation (1), we can estimate the amount of accreting material onto the collapsed star as shown in table 3(Jones et al. 1974). These estimation seem reasonable in various types of massive X-ray binary systems.

Table 3. Amount of accreting material onto the collapsed star(Jones et al. 1974)

Object	Mass($M_\odot$)	Radius(Km)	Accretion Rate($M_\odot$ yr^{-1})
White dwarf	1	10,000	$10^{-5} - 10^{-8}$
Neutron star	1	10	$10^{-8} - 10^{-11}$
Black hole	10	4	$10^{-8} - 10^{-12}$

The accretion onto the compact objects such as white dwarfs, neutron stars, or black holes can result from two types of mass transfer; stellar wind process(Davidson and Ostriker 1973, Hatchett and McCray 1977, Stella et al. 1986, Ho and Arons 1987a,b, Stevens 1988) and Roche lobe overflow process(Kopal 1959, Paczynski 1971, Pringle and Rees 1972, Lamb et al. 1973, Savonije 1978, 1979, Wang 1981, Taam and Meszaros 1987).

a) The optical counterparts

The optical component of X-ray binary system is important because it relates with the identification of the X-ray source. Bradt and McClintock(1983) categorized the X-ray binary system as massive, low-mass, and cataclysmic variables through studies of the ratio of X-ray(2-11 KeV) to optical(3000-7000 Å) luminosities. They found that the massive systems show a strong tendency to be pulsars and the low-mass systems show bursting or persistent-bright behaviors. The massive and low-mass systems are believed to contain neutron stars, and the cataclysmic variables to contain degenerate white dwarfs.

In the massive systems, the optical luminosity is dominated by the early-type star. To search for the massive optical companion, far-ultraviolet observation(1000-3000 Å) and He II line emission (4686 Å) have been used as the observation tools. It has been suggested that the He II emission (McClintock et al. 1975, Hutchings et al. 1977, Crampton et al. 1978) originates at a hot spot where accreting matter from the optical companion intersects the accretion disk. The ratio of X-ray to optical luminosity is in the range 10^{-5} to 10^{1}. The other probable parameters of massive systems are presented by Hutchings(1982).

In case of the low-mass system, the dominant visible light is associated with X-ray – heated gas and the ratio is in the range 10^{1}-10^{4}. Cowley(1982) noted the system properties of low-mass X-ray sources and subdivided them into four broad classes depending on their optical characteristics as follows.

- A bright disk dominates the optical spectrum(Sco X-1 type).
- The non-degenerate companion dominates the optical spectrum(Her X-1 and Cyg X-2 type).
- The strongly magnetic short period variables(AM Her type).
- The X-ray novae or transients(0620-00 type).

These low-mass systems have been discovered by ultraviolet excess, spectrophotometric data, and optical emission from the X-ray -heated gas.

b) Pulse profiles and Period variation

Binary X-ray sources exhibiting periodic X-ray pulsations are called binary X-ray pulsars. These objects are generally accepted as neutron stars and they are distinguished from non-periodic varying sources such as Cyg X-1. The first X-ray pulsation from Cyg X-1 was observed by Oda et al. (1971) and the periodic binary X-ray source Cen X-3 was discovered by the Uhuru satellite (Giacconi et al. 1971).

According to Joss and Rappaport(1984), the pulse periods of the known binary X-ray pulsars range over four decades in period, from 69ms(A 0538-66) to 835s(4U 0352+30). In addition Imamura et al.(1987) reported the possibility of the shortest periodicity in GX 339-4(1.13ms). Observed pulse profiles for 14 X-ray pulsars are presented in Figure 4. Some of these sources showed the variability with X-ray energy band(McClintock et al. 1976, Bradt et al. 1976). It is

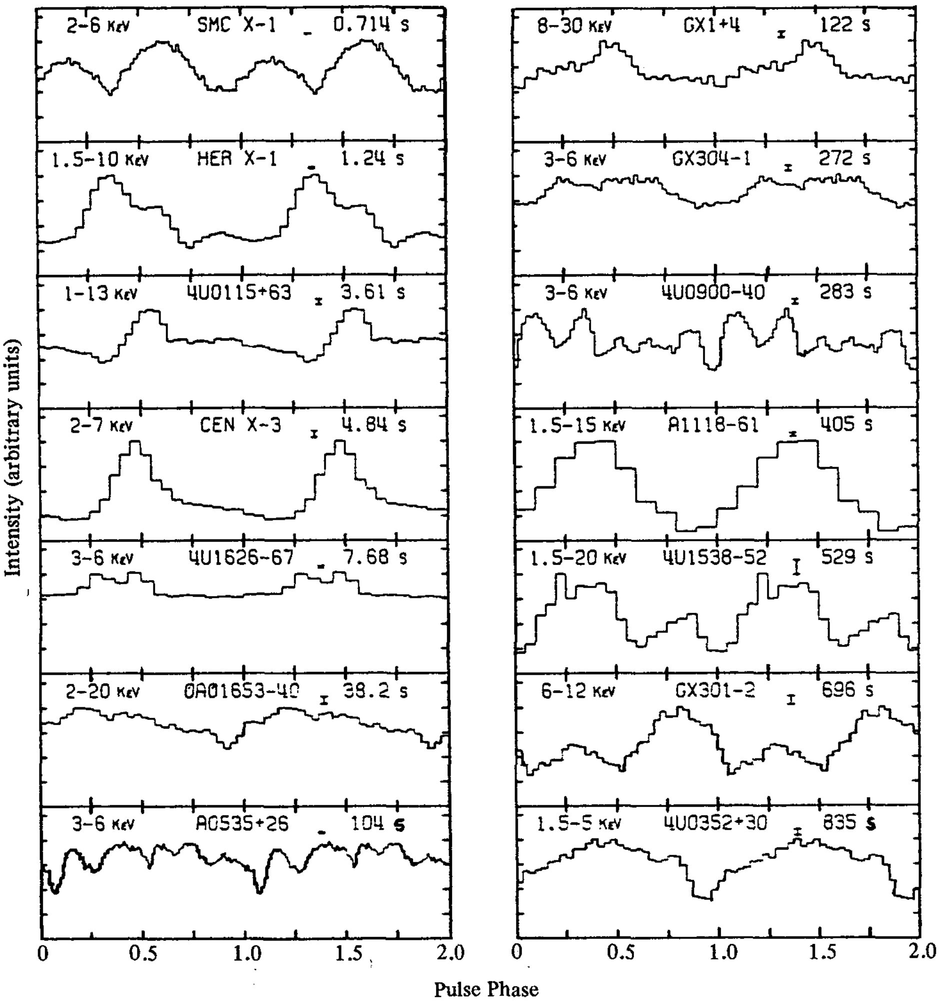

Fig. 4. Sample pulse profiles for 14 binary X-ray pulsars. The approximate pulse period and the energy interval are indicated for each pulsar (Rappaport and Joss 1981).

generally believed that the pulse shapes are related to the inclination between the line of sight and the rotation axis of an accreting, magnetized neutron star. Several models have been suggested such as pencil beam model, fan beam model, and Monte Carlo techniques to explain the observed pulse profiles(Joss and Rappaport 1984). However, the complex pulse shapes and X-ray energy dependence are not understood well as yet.

The pulse period variation with time has been found for binary X-ray pulsars as shown in Figure 5. From this figure, we know that five sources(SMC X-1, Her X-1, Cen X-3, GX 1+4, and 4U 0352+30) show a decreasing pulse period(spin up) continuously and the others display a periodic fluctuation(spin up and spin down).

On the basis of several works(Ghosh et al. 1977, Ghosh and Lamb 1978, 1979a, b, Davies et al. 1979, Davies and Pringle 1981, Wang 1981, Savonije and Papaloizou 1983, Stella et al. 1986), we can understand that these change are related with torques exerted by the matter accreting onto the neutron star. The rate of change of the intrinsic pulse period is related to the luminosity and the parameters of the compact star by the following relation(Ghosh and Lamb 1979b, Rappaport 1982, Joss and Rappaport 1984)

$$
\begin{aligned}
-\dot{P}/P = {} & 3 \times 10^{-5} (\xi V_r / V_{ff})^{1/7} (M/M_\odot)^{-10/7} (R_g / 10\,\mathrm{km})^{-2} (R/10\,\mathrm{km})^{6/7} \\
& \times (\mu / 10^{30} G\,\mathrm{cm}^3)^{2/7} (L_x / 10^{37}\,\mathrm{erg\,s}^{-1})^{6/7} (P/\mathrm{sec})\, y_r^{-1}, \quad \cdots\cdots\cdots\cdots\cdots\cdots \quad (2)
\end{aligned}
$$

where ξ represents the fractional solid angle subtended at the compact star by the infalling matter at the magnetopause; Vr/V_{ff} is the ratio of the average radial infall velocity of a particle to its free-fall velocity just outside the magnetopause; M, R, Rg and μ are the mass, radius, radius of gyration, and magnetic dipole moment of the compact star, respectively; and Lx is the accretion – driven luminosity. Ghosh and Lamb(1979b) presented that the mean spin up rate($\overline{-P/\dot{P}}$) of nine pulsating X-ray sources have range from 120±60(GX 301-2) to (3.3±0.6)x10^5 yr(Her X-1). For accreting neutron star models, this rate is identified as the rate of change of the stellar angular velocity. This rate gives valuable information both about the properties of the accretion flow pattern onto the star and about the properties of the star itself(Ghosh et al. 1977, Ghosh and Lamb 1979b).

The majority of the observed binary X-ray pulsars have massive companion with early spectral type(O, B or Be). Her X-1 and 4U 1626-67 have a low-mass companion star and GX 1+4 is identified with an M6 giant(Henrichs 1983).

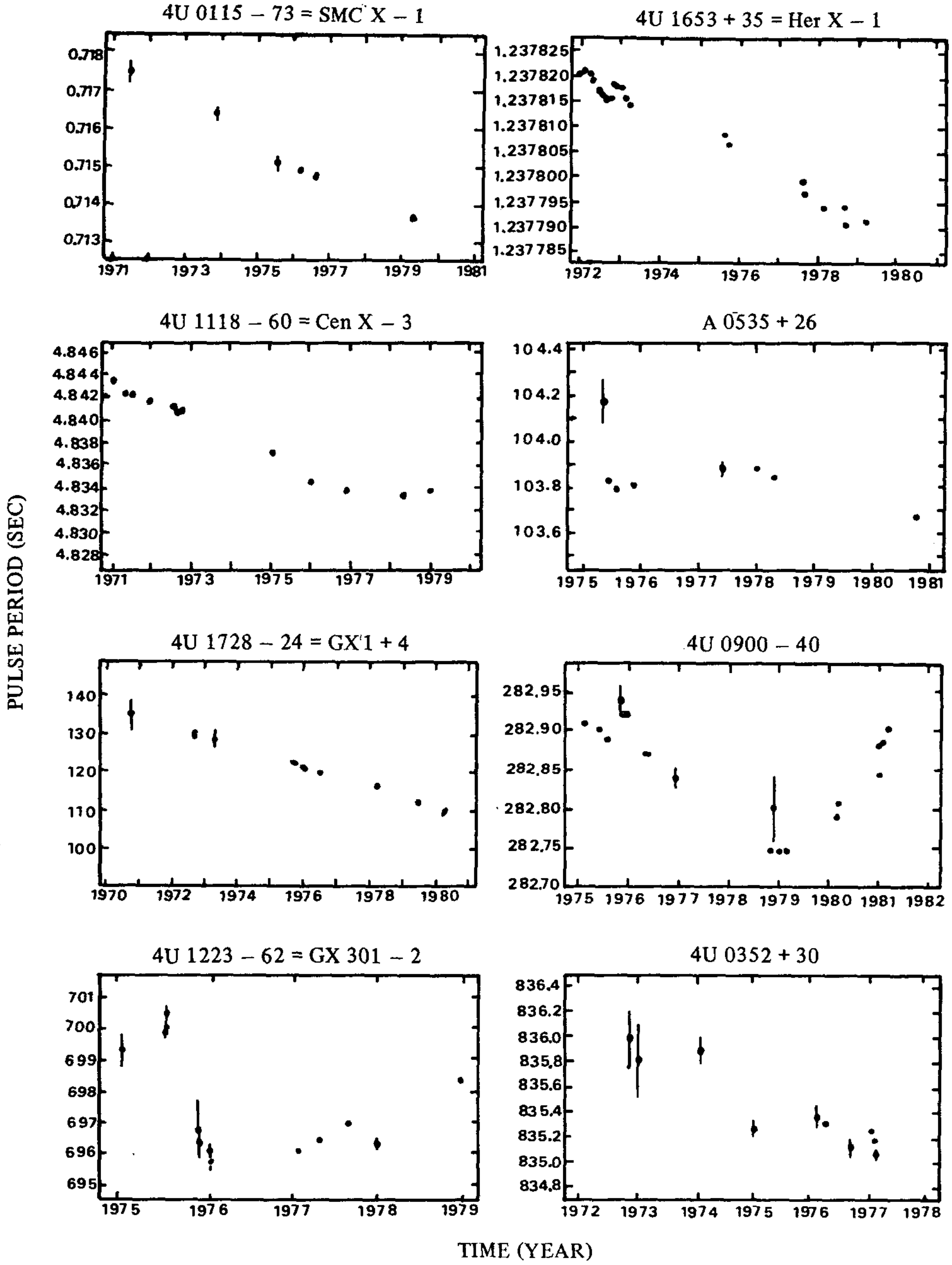

Fig. 5. Pulse period histories for 8 binary X-ray pulsars. The heavy dots are individual measurements of the pulse period and the vertical bars represent the uncertainties in the period determination (Rappaport and Joss, 1981).

IV. GBXs and Burster

One of the most interesting phenomena in galactic X-ray sources is the burst activity. The X-ray burst phenomenon was discovered by Grindlay et al.(1976). Since then, X-ray bursts have becomes the subject of intense observational and theoretical research.

X-ray bursters meet some criterions such as rise time less than a few seconds, duration from a few seconds to minutes, and burst recurrence property(Lewin and Joss 1977). These sources are concentrated in the direction of the galactic bulge and near the galactic plane. X-ray sources concentrating toward the galactic center and showing following characteristics are called galactic bulge sources as mentioned in section II(Lewin and Joss 1983).

- Lack of pulsations and eclipses
- Many of them produce X-ray bursts

Bursters show various burst profiles. The decay times are shorter at high energies than at low energies(Lewin and Joss 1977). This is related to the result of cooling process of the neutron star photosphere. According to Hoffman et al.(1978), X-ray bursters can be classified into two groups according to the profiles, type I bursts and type II bursts. Type I bursts occur at intervals from hours to days, and their spectra almost always soften during burst decay. Type II bursts occur at intervals of several seconds to minutes, and their spectra do not soften during burst decay.

There are many theoretical models(Henriksen 1976, Baan 1977, 1979, Wheeler 1977, Lamb et al. 1977, Liang 1977, Grindlay 1978, Lamb and Lamb 1978, Joss 1978, Apparao and Chitre 1979, Joss and Li 1980, Ayasli and Joss 1982, London et al. 1986, Fujimoto and Hanawa et al. 1987, Fujimoto and Sztajno et al. 1987, Babul and Paczynski 1987) suggested to explain for the bursts. It is generally accepted that thermonuclear flash models and accretion instability models are appropriate for the type I and type II bursts, respectively.

According to the thermonuclear flash model, the type I X-ray bursts are produced by thermonuclear flashes in the freshly deposited outermost layers of an accreting neutron star. The nuclear shell flashes in the envelope of accreting neutron stars are subject to variation in the neutron star mass and thermal state of the envelope(Hansen and Horn 1975, Lamb and Lamb 1978, Taam and Picklum 1978, Joss 1978, Taam 1981, Fujimoto et al. 1981). In case of the accretion-instability Lamb et al.(1977) suggested the existence of four distinct types of intermittent accretion flows onto neutron stars: compressional heating of matter at the boundary, Compton heating of matter at the boundary, Compton heating of matter far from the boundary, and radiation pressure. On the other hand, Baan(1977, 1979) presented the Kruskal-Schwarzschild instabilities at the magnetopause of an accreting and rotating neutron star for type II X-ray bursts.

Among the GBXs, quasi-periodic oscillations(QPO) in X-ray emission are newly discovered by van der Klis et al.(1985). QPO has been detected in several galactic bulge and burst X-ray sources including MXB 1730-335, GX 5-1, Sco X-1, and Cyg X-2(Berman and Stollman 1986, Middleditch and Priedhorsky 1986, Elsner et al. 1986, Stella et al. 1988 a, b). The observation of these phenomena provides an important tool for investigating the physical process occurring in several galactic bulge and burst X-ray sources(Elsner et al. 1987). There are various physical models proposed in order to explain the nature of QPO such as shot-noise model, beat-frequency modulated accretion model, and gravitational lens effect(Shaham 1986, Elsner et al. 1987, Wood et al. 1988, Stella et al. 1988 a, b, Elsner et al. 1988).

In our galaxy, it is known that twelve globular clusters contain X-ray sources and about nine of them produce X-ray bursts(Bradt and McClintock 1983). About six X-ray sources are located in the globular cluster center region(Grindlay et al. 1984). The precise determination of X-ray sources in globular clusters is very difficult because of their highly condensed core.

Globular cluster X-ray sources have been discussed by several authors to determine whether these sources are massive black holes or low-mass binary system(Clark 1975, Silk and Arons 1975, Fabian et al. 1975, Press and Teukolsky 1977, Krolik and Meiksin 1984, Krolik 1984). From the X-ray source positions and the detailed optical studies of eight globular clusters with HEAO-2 astronomical satellites, Grindlay et al.(1984) proposed some conclusions as follows.

- The distribution of the mass of the X-ray source is in the range of 0.9-1.9 M⊙.
- The gravitational potentials in these high-central density clusters are relatively smooth and the core is isothermal.
- The X-ray sources are compact binaries and are probably formed by tidal captures.

V. Summary

In this paper we reviewed the features of galactic X-ray sources. We also know that there exist extragalactic X-ray sources and the cosmic X-ray background, which are not understood well as yet. The X-ray observation with scientific satellites gives very useful high energy informations about the environment of close binary system, globular clustar center region, and the detailed physics taking place in the extreme conditions of gravity and magnetic field. Binary X-ray pulsars have provided an important tool for understandings of the mass transfer process in close binary systems and theoretical research of accretion flow pattern, instabilities in accretion disks, and history of spin-up and spin-down.

References

Apparao, K.M.V. and Chitre, S.M. 1979, *Ap. Space Sci.*, **63**, 125.

Ayasli, S. and Joss, P.C. 1982, *Astrophys. J.*, **256**, 637.

Baan, W.A. 1977, *Astrophys. J.*, **214**, 245.

__________. 1979, *Astrophys. J.*, **227**, 987.

Babul, A. and Paczynski, B. 1987, *Astrophys. J.*, **323**, 582.

Berman, N.M. and Stollman, G.M. 1986, *Astron. Astrophys.*, **154**, L 23.

Blumenthal, G.R. and Tucker, W.H. 1974, *Ann. Rev. Astron. Astrophys.*, **12**, 23.

Bradt, H.V., Apparao, K.M.V., Clark, G.W., Dower, R., Doxsey, R., Hearn, D.R., Jernigan, J.G., Joss, P.C., Mayer, W., McClintock, J. and Walter, F. 1977, *Nature*, **269**, 21.

Bradt, H., Mayer, W., Buff, J., Clark, G.W., Doxsey, R., Hearn, D., Jernigan, G., Joss, P.C., Laufer, B., Lewin, W., Li, F., Matilsky, T., McClintock, J., Primini, F., Rappaport, S. and Schnopper, H. 1976, *Astrophys. J.*, **204**, L 67.

Bradt, H.V.D. and McClintock, J.E. 1983, *Ann. Rev. Astron. Astrophys.*, **21**, 13.

Clark, G.W. 1975, *Astrophys. J.*, **199**, L 143.

Cooke, B.A., Ricketts, M.J., Maccacaro, T., Pye, J.P., Elvis, M., Watson, M.G., Griffiths, R.E., Pounds, K.A., Mchardy, I., Maccagni, D., Seward, F.D., Page, C.G. and Turner, M.J.L. 1978, *M.N.R.A.S.*, **182**, 489.

Cowley, A.P. 1982, *Galactic X-ray Sources*, ed. P.W. Sanford, P. Laskarideo and J. Salton (John Wiley and Sons: New York), pp.59-60.

Crampton, D., Hutchings, J.B. and Cowley, A.P. 1978, *Astrophys. J.*, **223**, L 79.

Davies, R.E., Fabian, A.C. and Pringle, J.E. 1979, *M.N.R.A.S.*, **186**, 779.

Davies, R.E. and Pringle, J.E. 1981, *M.N.R.A.S.*, **196**, 209.

Davidson, K. and Ostriker, J.P. 1973, *Astrophys. J.*, **179**, 585.

Elsner, R.F., Shibazaki, N. and Weisskopf, M.C. 1987, *Astrophys. J.*, **320**, 527.

__________________________________. 1988, *Astrophys. J.*, **327**, 742.

Elsner, R.F., Weisskopf, M.C., Darbro, W., Ramsey, B.D., Williams, A.C., Sutherland, P.G. and Grindlay, J.E. 1986, *Astrophys. J.*, **308**, 655.

Fabian, A.C., Pringle, J.E. and Rees, M.J. 1975, *M.N.R.A.S.*, **172**, 15P.

Forman, W., Jones, C., Cominsky, L., Julien, P., Murray, S., Peters, G., Tananbaum, H. and Giacconi, R. 1978, *Astrophys. J. Suppl.*, **38**, 357.

Fujimoto, M.Y., Hanawa, T. and Miyaji, S. 1981, *Astrophys. J.*, **246**, 267.

Fujimoto, M.Y., Hanawa, T., Iben, I. and Richardson, M.B. 1987, *Astrophys. J.*, **315**, 198.

Fujimoto, M.Y., Sztajno, M., Lewin, W.H.G. and Paradijs, J.V. 1987, *Astrophys. J.*, **319**, 902.

Ghosh, P. and Lamb, F.K. 1978, *Astrophys. J.*, **223**, L 83.

____________________. 1979a, *Astrophys. J.*, **232**, 259.

____________________. 1979b, *Astrophys. J.*, **234**, 296.

Ghosh, P., Lamb, F.K. and Pethick, C.J. 1977, *Astrophys. J.*, **217**, 578.

Giacconi, R. and Gursky, H. 1974, *X-ray Astronomy*, ed. R. Giacconi and H. Gursky(D. Reidel Pub. Co.: Dordrecht), pp.4-21.

Giacconi, R., Gursky, H., Kellogg, E., Schreier, E. and Tananbaum, H. 1971, *Astrophys. J.*, **167**, L 67.

Giacconi, R., Murray, S., Gursky, H., Kellogg, E., Schreier, E. and Tananbaum, H. 1972, *Astrophys. J.*, **178**, 281.

Giacconi, R., Murray, S., Gursky, H., Kellogg, E., Schreier, E., Matilsky, T., Koch, D. and Tananbaum, H. 1974, *Astrophys. J. Suppl.*, **27**, 37.

Grindlay, J.E. 1978, *Astrophys. J.*, **221**, 234.

Grindlay, J.E., Gursky, H., Schnopper, H., Parsignault D.R., Heise, J., Brinkman, A.C. and Schrijver, J. 1976, *Astrophys. J.*, **205**, L 127.

Grindlay, J.E., Hertz, P., Steiner, J.E., Murray, S.S. and Lightman, A.P. 1984, *Astrophys. J.*, **282**, L 13.

Gursky, H. and Schreier, E. 1975, *IAU Symposium*, No. 67, p.413.

Hansen, C.J. and Horn, H.M.V. 1975, *Astrophys. J.*, **195**, 735.

Hatchett, S. and McCray, R. 1977, *Astrophys. J.*, **211**, 552.

Henrichs, H.F. 1983, *Accretion-driven Stellar X-ray Sources*, ed. W.H.G. Lewin and E.P.J. van den Heuvel(Cambridge Univ. Press: Cambridge), pp.393-396.

Henriksen, R.N. 1976, *Astrophys. J.*, **210**, L 19.

Ho, C. and Arons, J. 1987a, *Astrophys. J.*, **316**, 283.

__________________. 1987b, *Astrophys. J.*, **321**, 404.

Hoffman, J.A., Marshall, H.L. and Lewin, W.H.G. 1978, *Nature*, **271**, 630.

Hutchings, J.B. 1982, *Galactic X-ray Sources*, ed. P.W. Sanford, P. Laskarideo and J. Salton(John Wiley and Sons: New York), pp.13-15.

Hutchings, J.B., Crampton, D., Cowley, A.P. and Osmer, P.S. 1977, *Astrophys. J.*, **217**, 186.

Imamura, J.N., Steiman-Cameron, T.Y. and Middleditch, J. 1987, *Astrophys. J.*, **314**, L 11.

Jones, C., Forman, W. and Liller, W. 1974, *Sky and Tel.*, **48**, No. 5, 289.

Joss, P.C. 1978, *Astrophys. J.*, **225**, L 123.

Joss, P.C. and Li, F.K. 1980, *Astrophys. J.*, **238**, 287.

Joss, P.C. and Rappaport, S.A. 1984, *Ann. Rev. Astron. Astrophys.*, **22**, 537.

Kopal, Z. 1959, *Close Binary Systems,* ed. Z. Kopal(Champan and Hall Ltd.: London), p.467.

Krolik, J.H. 1984, *Astrophys. J.*, **282**, 452.

Krolik, J.H. and Meiksin, A. 1984, *Astrophys. J.*, **282**, 466.

Lamb, F.K., Fabian, A.C., Pringle J.E. and Lamb, D.Q. 1977, *Astrophys. J.*, **217**, 197.

Lamb, D.Q. and Lamb, F.K. 1978, *Astrophys. J.*, **220**, 291.

Lamb, F.K., Pethick, C.J. and Pines, D. 1973, *Astrophys. J.*, **184**, 271.

Levine, A.M., Lang, F.L., Lewin, W.H.G., Primini, F.A., Dobson, C.A., Doty, J.P., Hoffman, J.A., Howe, S.K., Scheepmaker, A., Wheaton, W.A., Matteson, J.L., Baity, W.A., Gruber, D.E., Knight, F.K., Nolan, P.L., Pelling, R.M. Rothschild, R.E. and Peterson, L.E. 1984, *Astrophys. J. Suppl.*, **54**, 581.

Lewin, W.H.G. and Joss, P.C. 1977, *Nature*, **270**, 211.

Lewin, W.H.G. and Joss, P.C. 1983, *Accretion-drive Stellar X-ray Sources,* ed. W.H.G. Lewin and E.P.J. van den Heuvel(Cambridge Univ. Press: Cambridge), pp.41-46.

Liang, E.P.T. 1977, *Astrophys. J.*, **218**, 243.

London, R.A., Taam, R.E. and Howard, W.M. 1986, *Astrophys. J.*, **306**, 170.

Marshall, F.E., Boldt, E.A., Holt, S.S., Mushotzky, R.F., Pravdo, S.H., Rothschild, R.E. and Serlemitos, P.J. 1979, *Astrophys. J. Suppl.*, **40**, 657.

Markert, T.H., Winkler, P.F., Laird, F.N., Clark, G.W., Hearn, D.R., Sprott, G.F., Li, F.K., Bradt, H.V., Lewin, W.H.G. and Schnopper, H.W. 1979, *Astrophys. J. Suppl.*, **39**, 573.

McClintock, J.E., Rappaport, S., Joss, P.C., Bradt, H., Buff, J., Clark, G.W., Hearn, D., Lewin, W.H.G., Matilsky, T., Mayer, M. and Primini, F. 1976, *Astrophys. J.*, **206**, L 99.

McClintock, J.E., Canizares, C.R. and Tarter, C.R. 1975, *Astrophys. J.*, **198**, 641.

Mchardy, I.M., Lawrence, A., Pye, J.P. and Pounds, K.A. 1981, *M.N.R.A.S.*, **197**, 893.

Middleditch, J. and Priedhorsky, W.C. 1986, *Astrophys. J.*, **306**, 230.

Nugent, J.J., Jensen, K.A., Nousek, J.A., Garmire, G.P., Mason, K.O., Walter, F.M., Bowyer, C.S., Stern, R.A. and Riegler, G.R. 1983, *Astrophys. J. Suppl.*, **51**, 1.

Oda, M. 1987, *Physics Today,* **40**, No. 12, p.28.

Oda, M., Gorenstein, P., Gursky, H., Kellogg, E., Schreier, E., Tananbaum, H. and Giacconi, R. 1971, *Astrophys. J.*, **166**, L 1.

Paczynski, B. 1971, *Ann. Rev. Astron. Astrophys.*, **9**, 183.

Press, W.H.G. and Teukolsky, S.A. 1977, *Astrophys. J.*, **213**, 183.

Pringle, J.E. and Rees, M.J. 1972, *Astron. Astrophys.*, **21**, 1.

Rappaport, S. 1982, *Galactic X-ray Sources*, ed. P.W. Sanford, P. Laskarideo and J. Salton(John Wiley and Sons: New York), p.169.

Rappaport, S. and Joss, P.C. 1981, *X-ray Astronomy*, ed. R. Giacconi(D. Reidel Pub. Co.: Dordrecht), pp.123-125.

Savonije, G.J. 1978, *Astron. Astrophys.*, **62**, 317.

____________. 1979, *Astron. Astrophys.*, **71**, 352.

Savonije, G.J. and Papaloizou, J.C.B. 1983, *M.N.R.A.S.*, **203**, 581.

Shaham, J. 1986, *Astrophys. J.*, **310**, 780.

Silk, J. and Arons, J. 1975, *Astrophys. J.*, **200**, L 131.

Stella, L., Haberl, F., Lewin, W.H.G., Parmar, A.N., van der Klis, M. and van Paradijs, J. 1988a, *Astrophys. J.*, **327**, L 13.

Stella, L., Haberl, F., Lewin, W.H.G., Parmar, A.N., van Paradijs, J. and White, N.E. 1988b, *Astrophys. J.*, **324**, 379.

Stella, L., White, N.E. and Rosner, R. 1986, *Astrophys. J.*, **308**, 669.

Stevens, I.R. 1988, *M.N.R.A.S.*, **232**, 199.

Taam, R.E. 1981, *Astrophys. J.*, **246**, 257.

Taam, R.E. and Meszaros, P. 1987, *Astrophys. J.*, **322**, 329.

Taam, R.E. and Picklum, R.E. 1978, *Astrophys. J.*, **224**, 210.

van den Heuvel, E.P.J. 1983, *Accretion-driven Stellar X-ray Sources*, ed. W.H.G. Lewin and E.P.J. van den Hauvel(Cambridge Univ. Press: Cambridge), p.308.

van der Klis, M., Jansen, F., van Paradijs, J., Lewin, W.H.G., van den Heuvel E.P.J., Trumper, J.E. and Sztajno, M. 1985, *Nature*, **316**, 225.

Wang, Y.M. 1981, *Astron. Astrophys.*, **102**, 36.

Warwick, R.S., Marshall, N., Fraser, G.W., Watson, M.G., Lawrence, A., Page, C.G., Pounds, K.A., Ricketts, M.J., Sims, M.R. and Smith, A. 1981, *M.N.R.A.S.*, **197**, 865.

Wheeler, J.C. 1977, *Astrophys. J.*, **214**, 560.

Wood, K.S., Ftaclas, C. and Kearney, M. 1988, *Astrophys. J.*, **324**, L 63.

Wood, K.S., Meekins, J.F., Yentis, D.J., Smathers, H.W., Mcnutt, D.P., Bleach, R.D., Byram, E.T., Chubb, T.A. and Friedman, H. 1984, *Astrophys. J. Suppl.*, **56**, 507.

Żeldovich, Y.B. and Guseynov, O.H. 1966, *Astrophys. J.*, **144**, 840.