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van Paradijs, J.A.; White, N.E.

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THE GALACTIC DISTRIBUTION OF LOW-MASS X-RAY BINARIES

J. VAN PARADIJS[1,2] AND N. WHITE[3]
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ABSTRACT

We have analyzed the Galactic distribution of low-mass X-ray binaries (LMXBs) in which the accreting compact object is a neutron star. The rms value of their distances, z, to the Galactic plane equals ~1 kpc. This wide z-distribution cannot be explained by systemic velocities that increased as a result of sudden symmetric mass loss at the formation of the neutron star alone. Kick velocities imparted on the neutron star, following the radio pulsar velocity distribution recently derived by Lyne & Lorimer (1994) can account for the LMXB z-distribution. This distribution is consistent with formation of the neutron stars in LMXBs from direct collapse of a helium star and also from accretion-induced collapse of a white dwarf. The triple-star evolution proposed by Eggleton & Verbunt is not a dominant production mechanism for LMXBs.

Subject headings: Galaxy: kinematics and dynamics — stars: binaries: close — stars: neutron —X-rays: general

1. INTRODUCTION

In a low-mass X-ray binary (LMXB) a Roche-lobe-filling low-mass star transfers mass to a compact object (i.e., a neutron star or a black hole). The Galactic distribution of these binaries is determined by the average age of their parent population and by their dynamical evolution. Mass loss in the supernova explosion (which may be asymmetric) leads to a kick velocity of the compact object and thus of the system (if it is not disrupted). The velocity distribution of radio pulsars, as recently derived by Lyne & Lorimer (1994), shows that for neutron stars these kick velocities are very large (it is unknown whether black holes also obtain large kick velocities). Evidence for large velocities of LMXBs has been provided by Cowley, Hutchings, & Crampton (1988) from a statistical analysis of the systemic velocities obtained from optical observations for LMXBs with known orbital periods.

We here analyze the Galactic distribution of LMXBs in which the compact object is a neutron star (NS), in the framework of three evolutionary scenarios for their formation: (1) The LMXB progenitor is a binary in which a low-mass star is accompanied by a helium star sufficiently massive (i.e., $\geq 2.3\ M_\odot$; Habets 1985) that the end product of its evolution is a NS. (2) The immediate progenitor of the LMXB is a cataclysmic variable; the NS is formed by accretion-induced collapse of the accreting white dwarf. (3) The LMXB is the result of the evolution of a triple star; this scenario was proposed by Eggleton & Verbunt (1986) to explain the existence of LMXBs with black holes but may apply to those with NSs as well.

We make simple estimates of the velocities imparted on the LMXB systems at the formation of the NS, due to the sudden symmetric loss of mass from the system and due to a "kick" given to the NS, e.g., by asymmetric mass loss. We find that symmetric mass loss cannot account for the observed wide distribution of the distances of LMXBs from the Galactic plane.

[1] Astronomical Institute "Anton Pannekoek," University of Amsterdam; and Center for High Energy Astrophysics, Kruislaan 403, 1098SJ Amsterdam, The Netherlands.

[2] Physics Department, University of Alabama in Huntsville, Huntsville, AL 35899.

[3] Code 668, Laboratory for High Energy Astrophysics, Goddard Space Flight Center, Greenbelt, MD 20771.

2. SELECTION OF THE SAMPLE

LMXBs in which the compact star is a NS (NS-LMXBs) include X-ray burst sources (see Lewin, van Paradijs, & Taam 1993 for a review) and the Z- and atoll-type sources, many of which are bursters (Hasinger & van der Klis 1989). We have taken all known LMXBs outside globular clusters which are brighter than 10 μJy (van Paradijs 1995) but excluded those for which there is evidence that they harbor a black hole (i.e., nonbursting systems with either a very hard power-law spectrum extending above ~30 keV, or an ultrasoft component in their X-ray spectrum, or both; many of these are transients; see Tanaka & Lewin 1995). The sample includes transient sources which reached the 10 μJy level during outburst but were fainter at other times. The 10 μJy criterion was introduced in order not to contaminate the sample with unidentified weak sources (mainly concentrated in the Galactic center region) for which the LMXB nature is uncertain. We have made an exception for five sources which do not obey the flux criterion but for which the NS-LMXB nature is clear, either from the fact that they emit X-ray bursts (1323−619, 1744−300, 1905+000, 2129+470) or because it is a well-established accretion disk corona source (0921−630).

We list the sample of NS-LMXBs (64 in total) in Table 1. For this sample the rms latitude $b_{\rm rms} = 8\overset{\circ}{.}3$ and the rms longitude $l_{\rm rms} = 45°$.

3. GALACTIC DISTRIBUTION OF NS-LMXBs

3.1. *z-Distribution*

Distances to LMXBs can be estimated in several ways (see van Paradijs & McClintock 1994 for details).

1. Some X-ray bursts show evidence for photospheric radius expansion during the peak; the photon luminosity is then very close to the Eddington limit, which for NSs provides as good a standard candle as one may currently hope to obtain for them (see Lewin et al. 1993, and references therein).
2. Based on a successful radiation-hydrodynamic model of their ~6 Hz quasi-periodic oscillation (Fortner, Lamb, & Miller 1989; Lamb 1989) we have assumed that the X-ray luminosity of Z sources in their normal-branch spectral state (see Hasinger & van der Klis 1989) equals the Eddington limit;

TABLE 1

LMXBs with NS Accretors

0042+327	1632−477	1735−444	1758−205
0614+091	1636−536	1735−28	1803−245
0656−072	1642−455	1741.2−2859	1811−171
0748−676	1658−298	GC X-4	1812−12
0836−429	1702−429	1741−293	1813−140
0921−630	1702−363	GC X-2	1822−371
1254−690	1705−440	1742−289	1822−000
1323−619	1708−408	GC X-1	1826−238
1455−318	1711−339	1743.1−2843	1837+045
1516−569	1715−321	GX+0.2,−0.2	1905+000
1543−624	1724−356	1744−300	1908+005
1556−605	1728−337	1744−265	1916−053
1608−522	1728−169	1744−361	1918+146
1617−155	1728−247	1747−214	1940−04
1624−490	1730−220	GX+1.1,−1.0	2129+470
1627−673	1731−260	1758−250	2142+380

this is consistent with the flux distribution of the Z sources in the Galactic center region.

3. For LMXB transient sources with known orbital period, which in quiescence reveal the (optical) spectral signature of the low-mass secondary star, the distance can be estimated on the basis of the assumption that for low-mass stars the spectral type is uniquely related to visual surface brightness; the resulting distance estimate is weakly dependent on the secondary mass M_2 ($\propto M_2^{1/3}$).

Estimates of the distance, d, for 18 NS-LMXBs are given in Table 2. For these systems we can also determine the distribution of distances, z, from the Galactic plane; we find an rms value $z_{\rm rms} = 1.0$ kpc (for the bursters and the Z sources we find little difference, i.e., 1.2 kpc and 0.9 kpc, respectively).

Two objects (0748−676 and 2142+380 = Cyg X-2) have substantially larger values of z than the remaining sources; it is interesting to note that they are also the ones with the largest distances from the Galactic center (>10 kpc for both). This suggests that they have reached their high z-values because they underwent less deceleration in the z-direction than the sources closer to the Galactic center. If we exclude these two outliers, the remaining sources (most of which are located within 5 kpc of the Galactic center) give $z_{\rm rms} = 0.5$ kpc.

TABLE 2

LMXB Distance Estimates

Source	Type[a]	d (kpc)	z (kpc)
0748−676	B	7.6	−2.50
1455−314	T	1.6	+0.65
1516−569	B	10.9	0.00
1608−522	B	4.4	−0.07
1617−155	Z	2.2	+0.90
1636−536	B	5.5	−0.46
1642−455	Z	11.8	−0.02
1702−363	Z	9.2	+0.43
1715−321	B	6.1	+0.33
1728−337	B	5.7	−0.02
1735−444	B	9.2	−1.12
1758−250	Z	7.4	−0.13
1812−12	B	3.8	+0.15
1813−140	B	9.9	+0.23
1905+000	B	7.7	−0.50
1908+005	B	3.4	−0.24
1916−053	B	5.8	−0.85
2142+380	Z	12.4	−2.40

[a] B = Eddington limited X-ray bursts; T = transient; Z = Z source.

The average value of the projected distances of burst sources along the line to the Galactic center equals 5.2 ± 0.7 kpc, i.e., less than the Galactic center distance of ∼8 kpc (Reid 1993). We consider it unlikely that we have underestimated the peak luminosity of bursts with radius expansion by a factor ∼2 (see, e.g., Lewin et al. 1993); rather, we think that the weakest burst sources at the far side of the Galaxy have not been sampled as well as the nearby ones. We do not expect this effect to influence the observed z-distribution much.

3.2. *Radial Distribution*

To get some information on the radial distribution of NS-LMXBs in the Galaxy we have made Monte Carlo simulations of their sky distribution, assuming that their Galactic distribution can be described by an axisymmetric function $\rho(r, z) = \exp(-r/r_0)\ \exp\ (-z/z_0)$. If there were no selection effect against distant systems the observed value of $l_{\rm rms}$ would correspond to $r_0 \sim 4.5$ kpc. For a sample of 64 sources the 90% confidence level range on this value is 2.8–6.4 kpc. If sources on the far side of the Galactic center are underrepresented in the observed sample, this value of r_0 is an overestimate. This scale length is consistent with that of the old disk population in the Galaxy (see, e.g., Fux & Martinet 1994, and references therein).

4. DISCUSSION

4.1. *Encounters with Molecular Clouds*

The z-distribution of the NS-LMXBs is wider than expected for members of the old Galactic disk population (age $\sim 10^{10}$ yr). These will have been secularly accelerated by encounters with massive molecular clouds. According to the results of Wielen & Fuchs (1985), after 10^{10} yr this mechanism leads to a velocity dispersion in the z-direction of ∼30 km s^{-1}; using the z-dependence of the acceleration perpendicular to the Galactic plane in the solar neighborhood (Oort 1965; Kuijken & Gilmore 1989) shows that this velocity corresponds to a *maximum* height above the Galactic plane of ∼400 pc. Thus, this mechanism cannot explain the observed z-distribution of NS-LMXBs.

4.2. *System Velocities Acquired at NS Formation*

The large z-velocities required for the observed value of $z_{\rm rms}$ can be caused by sudden symmetric mass loss at the formation of the NS or by a kick velocity of the NS due to an asymmetry in the supernova explosion.

4.2.1. *Sudden Symmetric Mass Loss*

We discuss sudden symmetric mass loss in an LMXB progenitor where the NS is formed by the direct collapse of a helium star. We assume that, just before the NS is formed, the binary consists of the current secondary star with mass $M_{\rm sec} = m_{\rm sec} M_\odot$ and a helium star with mass $M_{\rm He} = m_{\rm He} M_\odot$, in a circular orbit with separation a_0 and orbital period P_0. The total system masses before and after the sudden mass loss are M_0 and M, respectively; we define $f = M/M_0$. Then after the sudden mass loss the semimajor axis a, orbital period P, and eccentricity e are given by $a/a_0 = f/(2f-1$, $P/P_0 = f/(2f-1)^{3/2}$, and $e = (1-f)/f$ (see, e.g., Dewey & Cordes 1987). The system is disrupted for $f \leq 0.5$. If it is not, the system velocity of the binary becomes $v_{sys} = ev_{He} = v_{He}(1-f)/f$, where v_{He} is the orbital velocity (relative to the center of mass) of the presupernova helium star.

For the postsupernova system (which will become the LMXB) we take $M_{NS} = 1.4\ M_\odot$. Current mass estimates for secondaries in LMXBs indicate that $m_{sec} < 1$; however, with stable mass transfer possible for m_{sec} up to 1.5, we have taken m_{sec} in the range 0.2–1.5. To keep the system bound after the supernova explosion, M_{He} should be less than $M_{He,max} = 2.8\ M_\odot + M_{sec}$. In our estimates we have taken an average helium star mass, weighted according to Salpeter's initial mass function in the range 2.3 $M_\odot$ to $M_{He,max}$. This weighting was taken because over the mass range 9–30 $M_\odot$ the ratio of the mass of the helium core after the main-sequence phase to the initial main-sequence mass is approximately constant. We find that the average helium star mass can be well described by $\langle M_{He}\rangle = 2.55\ M_\odot + 0.35\ M_{sec}$. The corresponding values of f are between 0.57 and 0.64; the postsupernova system velocities are between 0.56 and 0.75 times the orbital velocity of the helium star.

The orbital velocity of the helium star can be related to that of the later X-ray source (v_X) if we assume that during the circularization of the (eccentric) postsupernova orbit the orbital angular momentum is conserved. This implies that $a(1-e^2)$ = constant and $2\pi a/P \propto (1-e^2)^{1/2}$. From the above expressions for the effect of sudden mass loss on the orbital parameters we find $v^* \equiv 2\pi a/P = (2\pi a_0/P_0)(2f-1)^{1/2}$, and for the relative velocity of the components of the X-ray binary $v' = (2\pi a/P)f(2f-1)^{-1/2} = f(2\pi a_0/P_0)$. Thus $v_X/v_{He} = (M_0/M)f = 1$, and for the expected system velocity we find $v_{sys} = v_X(1-f)/f$.

For a Roche-lobe-filling secondary star (assumed to have a main-sequence structure, with radius proportional to mass) the velocity of the X-ray source (relative to the center of mass of the LMXB) $v_X = (300\ \mathrm{km\ s^{-1}})(M_{sec}/M)^{2/3}$ (unless the secondary fills its Roche lobe when the orbit is just circularized, this value of v_X, as well as that of v_{sys}, see below, is an overestimate). The resulting expected system velocities of the LMXB, caused by sudden symmetric mass loss at the formation of the NS, range between ~55 and ~110 km s^{-1} (for m_2 between 0.2 and 1.5).

For a uniform distribution of secondary masses between 0.2 and 1.5 $M_\odot$ we obtain an average $v_{sys} = 94$ km s^{-1}. The average z-component, v_z, is 55 km s^{-1}; in the solar neighborhood this would correspond to a *maximum* height above the Galactic plane of ~900 pc and $z_{rms} \sim 650$ pc (Oort 1965; Kuijken & Gilmore 1989). However, most of the LMXBs are located in the central regions of the Galaxy, where the deceleration in the z-direction is substantially larger than in the solar neighborhood (e.g., according to the model of Carlberg & Innanen 1987, by a factor of ~2.5–4 for Galactocentric distances between 0 and 5 kpc); therefore, the above value of v_z corresponds to an expected z_{rms} of at most ~250 pc, substantially below the observed value (i.e., 0.5 kpc, if we exclude Cyg X-2 and 0748−676; see § 3.1).

We conclude that symmetric mass loss alone cannot explain the observed z-distribution of NS-LMXBs.

4.2.2. *NS Kick Velocities*

To estimate system velocities caused by a NS kick velocity we have used the expression given by Hills (1983, eq. [22]) to calculate the probability p that the binary system remains bound when a mass $\Delta M = M_0(1-f)$ is suddenly lost and a kick velocity ΔV is imparted on the neutron star:

$$2p - 1 = \frac{1 - 2\Delta M/M_0 - (\Delta V/V_c)^2}{2\Delta V/V_c}. \quad (1)$$

Here we have assumed that the presupernova orbit is circular; V_c is the relative velocity of this orbit. Putting $x = \Delta V/V_c$, we find that for $x > x_{max} = 1 + [1 + (1 - 2\Delta M/M_0)]^{1/2}$ the system is always disrupted (then $p = 0$); for $x < x_{min} = x_{max} - 2$ it always remains bound (then $p = 1$).

For a given value of $\Delta M/M_0$, $\Delta V/V_c$ is a function of p. For an assumed value of V_c this allows us to calculate an average system velocity, $\langle V_{sys}\rangle$, through

$$\langle V_{sys}\rangle = \frac{\int_0^{\Delta V_{max}} F(\Delta V)p(\Delta V)V'\,d(\Delta V)}{\int_0^{\Delta V_{max}} F(\Delta V)p(\Delta V)\,d(\Delta V)}. \quad (2)$$

For the NS kick velocity distribution $F(\Delta V)$ we have taken the observed (three-dimensional) velocity distribution of velocities of radio pulsars as presented by Lyne & Lorimer (1994, Fig. 2). The velocity scale of this distribution is uncertain by ~35% (M. Bailes 1994, private communication).

In the velocity V' we have incorporated, in an approximate fashion, the effects of symmetric mass loss, by taking the average value of the length of the velocity vector that combines the system velocities due to this mass loss ($\boldsymbol{v}_{ml}$; this is the velocity calculated in § 4.2.1) and due to the kick imparted on the NS [$\boldsymbol{v}_k = (M_{NS}/M)\Delta V$] according to

$$V' = \frac{\int_0^{\theta_{max}} y(\theta)\sin\theta\,d\theta}{\int_0^{\theta_{max}} \sin\theta\,d\theta}, \quad (3)$$

where $y^2(\theta) = v_k^2 + v_{ml}^2 + 2v_k v_{ml}\cos\theta$ and θ is the angle between $\boldsymbol{v}_{ml}$ and $\boldsymbol{v}_k$. For $\theta > \theta_{max}$ the system is disrupted; θ_{max} is related to p according to $\cos\theta_{max} = 1 - 2p$.

The orbital periods of a large majority of LMXBs are in the range 3 hr to 1 day. The results of Hills (1983) indicate that combined sudden symmetric mass loss and a kick velocity of the NS tends to decrease the separation of the (assumed circular) presupernova orbit, but not by a large factor. We will assume that the majority of the presupernova orbits had periods in the range 6 hr to 60 days. For a presupernova orbit with a period of P_{hr} hr one has $V_c = (615\ \mathrm{km\ s^{-1}})(M_0/M_\odot)^{1/3} P_{hr}^{-1/3}$. For m_{sec} in the range 0.2–1.5 we have to a good approximation $(M_0/M_\odot)^{1/3} = 1.5$. We have therefore taken V_c in the range 80–500 km s^{-1}.

We find that for m_{sec} in the range 0.2–1.5 (with corresponding values of $\Delta M/M_0$ in the range 0.36–0.43), $\langle V_{sys}\rangle$ ranges between ~240 and 320 km s^{-1} (for $V_c = 500$ km s^{-1}) and between ~110 and 120 km s^{-1} (for $V_c = 80$ km s^{-1}). The net effect of including symmetric mass loss is to increase the value of $\langle V_{sys}\rangle$ above that expected for NS kick velocities alone; this is so because for the surviving binaries the NS kick velocities tend to be directed opposite to the NS orbital velocity (i.e., in the direction of $\boldsymbol{v}_{ml}$). For increasing values of m_2 the effect of mass loss becomes relatively more important, mainly because the orbital velocity of the NS progenitor increases.

In the solar neighborhood the corresponding average z-velocities (range ~65–180 km s^{-1}) correspond to values of z_{rms} between ~1 and ~6 kpc. These are larger than the observed value (see § 3); to reproduce the observed value of z_{rms}, the required acceleration g_z in the z-direction would have to be larger by a factor of 1–6 than in the solar neighborhood (by a factor of 2–12 if we do not include Cyg X-2 and 0748−676 in our estimate of z_{rms}; see § 3.1). Since most LMXBs are found in the inner ∼4 kpc, this requirement on g_z can probably be met without problems (e.g., the Galactic model of Carlberg & Innanen 1987 provides a factor of 2.5–4 for Galactocentric distances less than 5 kpc).

We conclude that the observed z-distribution of NS-LMXBs requires that the NSs formed in LMXBs receive a kick velocity; the required kick velocity distribution is consistent with that of radio pulsars (Lyne & Lorimer 1994).

4.3. *Accretion-induced Collapse*

According to this evolutionary model the NS is formed when the mass of an accreting white dwarf exceeds the Chandrasekhar limit; as the NS forms, ∼0.2 $M_\odot$ in gravitational mass is lost. With a white dwarf mass of 1.4 $M_\odot$ and secondary masses in the range 0.2–1.5 $M_\odot$ the corresponding value of $f = M/M_0$ is in the range 0.88–0.93. Following the argument in § 4.2.1 we then find for the system velocity $v_{sys} = (0.07–0.14)v_X$, much smaller than for systems in which the NS was formed by the direct collapse of a helium star. Thus, also in the case of accretion-induced collapse, symmetric mass loss alone is insufficient to account for the observed z-distribution of NS-LMXBs. If accretion-induced collapse is an important formation mechanism of neutron stars in LMXBs this formation must therefore also lead to a large kick velocity of the NS.

Following the argument in the previous section, we have calculated the average system velocities for NS-LMXBs formed this way; the assumption underlying this calculation is that the distribution of kick velocities imparted on the NSs is the same as the radio pulsar velocity distribution (Lyne & Lorimer 1994). We find that for V_c between 80 and 500 km s^{-1} the average v_{sys} ranges are ∼80–300 km s^{-1} (for $m_{sec} = 0.2$) and ∼45–170 km s^{-1} (for $m_{sec} = 1.5$), i.e., somewhat smaller than for the case of direct helium star collapse (due to the much smaller effect of mass loss). The corresponding values of z_{rms} range from ∼0.5 to 5 kpc; thus, LMXB formation by accretion-induced collapse appears to be consistent with the kinematic properties of LMXBs.

4.4. *Triple-Star Evolution*

According to this scenario (Eggleton & Verbunt 1986) the compact star is formed in a massive close binary (analogous to a high-mass X-ray binary [HMXB]), which is accompanied by a distant third companion. After the initial onset of the X-ray binary phase of this inner binary, a common-envelope phase ensues which leads to the formation of a Thorne-Zytkow object (i.e., a red supergiant with a NS in the core). If the third star is close enough it will be caught in the envelope of this supergiant and spiral inward. The outcome may be a binary consisting of the compact star and the low-mass companion (the original third star).

At the only occasion in this evolutionary sequence when a kick velocity is imparted on the system, the forming compact star is a member of a massive (inner) binary. Observations of HMXBs (Van Oijen 1989) show that these objects are runaway objects indeed, but their velocities are fairly small (∼30 km s^{-1}); the corresponding *maximum* distances to the Galactic plane (∼400 pc in the solar neighborhood, substantially less in the more central regions of the Galaxy) are too small to explain the z-distribution of LMXBs. We therefore conclude that this triple-star evolution is not a dominant formation mechanism for LMXBs.

5. CONCLUSIONS

We have considered several possible mechanisms to explain the wide Galactic z-distribution of NS-LMXBs and concluded that secular acceleration by interactions with massive molecular clouds, and systemic velocities due to sudden mass loss, cannot explain the observed z-distribution. This distribution requires that the NSs formed in LMXB receive a kick velocity; the required kick velocity distribution is consistent with that observed for radio pulsars (Lyne & Lorimer 1994). LMXB formation by accretion-induced collapse of a white dwarf appears to be consistent with the kinematic properties of LMXBs. Triple-star evolution is not a dominant formation mechanism for LMXBs.

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