LOW-MASS X-RAY BINARIES, MILLISECOND RADIO PULSARS, AND THE COSMIC STAR FORMATION RATE

NICHOLAS E. WHITE AND PRANAB GHOSH

Laboratory for High Energy Astrophysics, NASA Goddard Space Flight Center, Greenbelt, MD 20771

Received 1998 June 6; accepted 1998 July 2; published 1998 July 27

ABSTRACT

We report on the implications of the peak in the cosmic star formation rate (SFR) at redshift $z \approx 1.5$ for the resulting population of low-mass X-ray binaries (LMXBs) and for that of their descendants, the millisecond radio pulsars (MRPs). Since the evolutionary timescales of LMXBs, their progenitors, and their descendants are thought to be significant fractions of the time interval between the SFR peak and the present epoch, there is a lag in the turn-on of the LMXB population, with the peak activity occurring at $z \approx 0.5–1$. The peak in the MRP population is delayed further, occurring at $z \approx 0.5$. We show that the discrepancy between the birthrate of LMXBs and the birthrate of MRPs, found under the assumption of a steady state SFR, can be resolved for the population as a whole when the effects of a time-variable SFR are included. A discrepancy may persist for LMXBs with short orbital periods, although a detailed population synthesis will be required to confirm this. Furthermore, since the integrated X-ray luminosity distribution of normal galaxies is dominated by X-ray binaries, it should show strong luminosity evolution with redshift. In addition to an enhancement near the peak ($z \approx 1.5$) of the SFR due to the prompt turn-on of the relatively short-lived massive X-ray binaries and young supernova remnants, we predict a second enhancement by a factor of $\sim 10$ at a redshift between $\sim 0.5$ and $\sim 1$ due to the delayed turn-on of the LMXB population. Deep X-ray observations of galaxies out to $z \approx 1$ by the Advanced X-Ray Astrophysics Facility will be able to observe this enhancement and, by determining its shape as a function of redshift, will provide an important new method for constraining evolutionary models of X-ray binaries.

Subject headings: binaries: close — galaxies: evolution — pulsars: general — stars: evolution — stars: formation — X-rays: galaxies — X-rays: stars

1. INTRODUCTION

It has recently been shown that the cosmic star formation rate (SFR) increases with redshift, reaching a peak $\sim 10$ times higher than the current rate in the redshift interval $1–2$ (Lilly et al. 1996; Madau et al. 1996; Madau, Pozzetti, & Dickinson 1998a, hereafter MPD; Madau, Della Valle, & Panagia 1998b, hereafter MVP). In this Letter, we report on the interesting implications of this for the evolution of low-mass X-ray binaries (LMXBs), for that of their descendants, the millisecond radio pulsars (MRPs), and also for the well-known LMXB-MRP “birthrate problem” (see Bhattacharya 1995 and references therein). Similar considerations of the implications of the cosmic SFR for the evolution of the cosmic supernova rates have recently been undertaken (MVP). In essence, the LMXB-MRP birthrate problem stems from the observation that, for estimated numbers $N_{\text{LMXB}} \sim 100$ and $N_{\text{MRP}} \sim 10^4$ in our Galaxy, and for expected lifetimes $\tau_{\text{LMXB}} \sim 10^8–10^9$ yr and $\tau_{\text{MRP}} \sim 10^3–10^5$ yr, the steady state birthrate of MRPs, $N_{\text{MRP}}/\tau_{\text{MRP}}$, exceeds that of LMXBs, $N_{\text{LMXB}}/\tau_{\text{LMXB}}$, by $\sim 10$ (Kulkarni & Narayan 1988, hereafter KN; Cotè & Pylyser 1989, hereafter CP; Lorimer 1995, hereafter L95). Many of the suggested solutions to the problem include (a) accretion-induced collapse of a white dwarf to a neutron star, (b) much shorter values of $\tau_{\text{LMXB}}$ for the short-period LMXBs (i.e., those with orbital periods $\leq 3$ days, say, following the definition of KN), due, e.g., to X-ray irradiation of the low-mass companion (Tavani 1991, hereafter T91), and (c) the possibility that pulsars can be born with low magnetic fields and millisecond periods.

We show here that steady state arguments do not generally apply to evolving LMXB and MRP populations with a time-dependent global SFR peaking at $z \approx 1.5$, since this peak propagates through the LMXB and MRP populations at smaller redshifts and causes an enhanced MRP population at the present epoch. Indeed, except in special circumstances outlined in § 2, there is no basis for expecting an equality between the rates $N_{\text{MRP}}/\tau_{\text{MRP}}$ and $N_{\text{LMXB}}/\tau_{\text{LMXB}}$. We present evolutionary calculations showing that the expected number ratio, $N_r \equiv N_{\text{MRP}}/N_{\text{LMXB}}$, and rate ratio, $R_r \equiv (N_{\text{MRP}}/\tau_{\text{MRP}})/(N_{\text{LMXB}}/\tau_{\text{LMXB}})$, at $z = 0$ are in agreement with the currently observed values for the whole population. However, there may still be a discrepancy for the short-period systems. We consider other observational tests of our model and indicate how observations of galaxies in the redshift range $0.5–1.0$ by Advanced X-Ray Astrophysics Facility (AXAF) can constrain models for the evolution of X-ray binaries.

2. EVOLUTION OF LMXBS AND MRPS WITH VARIABLE SFR

The standard evolutionary scenario for the majority of LMXBs and MRPs begins with a primordial binary containing a massive OB star and a low-mass star (see, e.g., Webbink, Rappaport, & Savonije 1983, hereafter WRS; Kalogera & Webbink 1996, 1998). The massive star rapidly evolves to the point of becoming a supernova (SN), resulting in the formation of a post-SN binary (PSNB) consisting of a neutron star with a low-mass companion, which turns into a LMXB when the latter attains Roche lobe contact, because of either nuclear evolution or orbital decay by gravitational radiation and magnetic braking. This, in turn, produces a recycled MRP at the end of mass transfer. We demonstrate here the basic effects of a time-variable SFR on the above scenario. In this introductory work, we do not consider the LMXBs and MRPs found in globular clusters, where tidal capture of neutron stars in close encounters with stars causes an excess of LMXBs relative to the overall Galactic population.

---

1 Senior NAS/NRC Resident Research Associate.

2 On leave from the Tata Institute of Fundamental Research, Bombay 400 005, India.
Fig. 1.—Evolution of PSNB, LMXB, and MRP populations in response to a time-variable cosmic SFR. Logarithms of the number densities of PSNBs (dotted line), LMXBs (dash-dotted line), and MRPs (solid line) against the redshift are shown. The SFR of Madau et al. is also shown (dashed line) for reference. Each panel displays the results of an evolutionary calculation with input timescales \( \tau_{\text{PSNB}}, \tau_{\text{LMXB}}, \) and \( \tau_{\text{MRP}} \) written at the top of the panel and output values of the number ratio, \( N_i = n_{i,\text{out}}/n_{i,\text{ini}} \), and rate ratio, \( R_i = (N_i,\text{out})/(N_i,\text{ini}) \), at \( z = 0 \) written at the bottom. Panel a represents a typical result for the whole population of LMXBs and MRPs, with \( R_i \approx 1 \). Panel b represents a typical result for short-period systems (see text), with \( R_i > 1 \). Panel c shows the results of postulating an unusually short LMXB lifetime, due, e.g., to X-ray irradiation of the secondary in close binaries (see text). Finally, panel d illustrates the approach to an asymptotic state for all populations, as described in the text, obtained by choosing unrealistically short values for the timescales \( \tau_{\text{PSNB}}, \tau_{\text{LMXB}}, \) and \( \tau_{\text{MRP}} \).

The evolutions of populations of PSNBs, LMXBs, and MRPs in response to a time-dependent star formation rate SFR(t) are given by

\[
\frac{dn_{\text{PSNB}}(t)}{dt} = \alpha \text{SFR}(t) - \frac{n_{\text{PSNB}}(t)}{\tau_{\text{PSNB}}},
\]

\[
\frac{dn_{\text{LMXB}}(t)}{dt} = \frac{n_{\text{PSNB}}(t)}{\tau_{\text{PSNB}}} - \frac{n_{\text{LMXB}}(t)}{\tau_{\text{LMXB}}},
\]

\[
\frac{dn_{\text{MRP}}(t)}{dt} = \frac{n_{\text{LMXB}}(t)}{\tau_{\text{LMXB}}} - \frac{n_{\text{MRP}}(t)}{\tau_{\text{MRP}}},
\]

In equation (1), SFR(t) is that given by MPD and MVP, with the SFR evolving on a timescale \( \tau_{\text{SFR}} \approx 6.4 \times 10^4 \) yr; for all calculations reported here, we have used the analytic approximation (accurate to within 5%) to the SFR given by MVP, which is shown in Figure 1. Furthermore, \( \alpha \) is a coefficient that determines the rate of formation of PSNBs per unit SFR.

Assuming that the time required by massive newborn stars to evolve to the point of supernova is small compared with all other evolutionary timescales in the problem, i.e., \( \tau_{\text{SFR}} \gg \tau_{\text{PSNB}} \), \( \tau_{\text{LMXB}} \), and \( \tau_{\text{MRP}} \) (an excellent approximation in view of the value of \( \tau_{\text{SFR}} \) given above and the values of \( \tau_{\text{PSNB}} \), \( \tau_{\text{LMXB}} \), and \( \tau_{\text{MRP}} \) given below), \( \alpha \) is given approximately by \( \alpha = f_{\text{binary}} f_{\text{SN}} / \tau_{\text{SN}} \). Here \( f_{\text{binary}} \) is the fraction of all stars in binaries, \( f_{\text{SN}} \) is that fraction of primordial binaries having the correct range of stellar masses and orbital periods for evolving into PSNBs capable of producing LMXBs (Kalogera & Webbink 1998, hereafter KW98), and \( f_{\text{SN}} \) is that fraction of the latter binaries that survives the supernova. The actual value of \( \alpha \), which sets the overall scale for the sizes of the populations \( n_{\text{PSNB}}, n_{\text{LMXB}}, \) and \( n_{\text{MRP}} \) relative to that of the SFR, is irrelevant for this study, since we are only interested in the relative sizes of \( n_{\text{LMXB}} \) and \( n_{\text{MRP}} \) here.

Figure 1 shows the evolution of PSNBs, LMXBs, and MRPs described by equations (1)–(3): we have displayed our results in terms of the redshift \( z \), which is related to the cosmic time \( t \) by \( t_0 = (z + 1)^{-5/2} \), where \( t_0 \) is \( t \) in units of \( 10^9 \) yr, and a value of \( H_0 = 50 \) km s\(^{-1}\) Mpc\(^{-1}\) has been used (MPD). Our choices of representative values of \( \tau_{\text{PSNB}}, \tau_{\text{LMXB}}, \) and \( \tau_{\text{MRP}} \) come from the following considerations. The distribution of \( \tau_{\text{PSNB}} \) with orbital period is rather broad, has a peak in the range \((1–2) \times 10^5 \) yr, and is somewhat dependent on supernova kick velocity and common-envelope evolution efficiency (V. Kalogera 1998, private communication). The expected range of \( \tau_{\text{LMXB}} \) values has been discussed extensively in the literature on the birthrate problem (KN; CP; T91; L95). The standard WRS mass transfer time, \( \tau_{\text{MRP}} \approx 1.1 \times 10^7 P(d) \) yr, has been widely used, where \( P(d) \) is the initial orbital period of the
LMXBs in days, and, to ameliorate the problem for short-period LMXBs, it has been suggested that the effects of X-ray irradiation of the low-mass companion may reduce \( \tau_{LMXB} \) to \( \sim 10^3 \) yr in these systems (T91; L95). For \( \tau_{MRP} \), we used values based on the compilation by Camilo, Thorsett, & Kulkarni (1994), which suggests \( \tau_{MRP} \) in the range \( 3 \times 10^5 - 3 \times 10^{10} \) yr.

3. DISCUSSION

The results shown in Figures 1a–1c clearly demonstrate that the approximately gigayear timescales involved in the evolution of PSNBs, LMXBs, and MRPs lead to substantial time lags in the peaks of their populations behind the peak in the SFR. The LMXB peak is delayed by several gigayears relative to the SFR peak and appears in the redshift range \( z \sim 0.5 - 1 \). The MRP peak is delayed even further, appearing at redshifts \( \leq 0.5 \) (including the current epoch). Thus, although the previous work of KN and others assumed steady state conditions while comparing the birthrates of MRPs and LMXBs, we now see that this assumption is not correct in general in a universe with a time-dependent cosmic SFR. There are, however, two limiting cases where this assumption will still apply. The first occurs when an asymptotic state is reached for all populations, which cases where this assumption will still apply. The first occurs when an asymptotic state is reached for all populations, which happens at times much longer than all evolutionary timescales in the problem, as illustrated by the case shown in Figure 1d. However, it must be clear that such a situation cannot occur within the current age of the universe for any realistic choice of \( \tau_{PSNB} \), \( \tau_{LMXB} \), and \( \tau_{MRP} \), which is why we had to assume unrealistically short timescales for Figure 1d. This possibility is thus of little relevance to the present universe, unless our current understanding of LMXB and MRP evolution is completely wrong. The second situation obtains when, for sufficiently large values of \( \tau_{MRP} \), the present epoch (\( z = 0 \)) happens to be at or near the maximum of the MRP evolution, where \( \partial n_{MRP}(t)/\partial t = 0 \) (see eq. [3]), so that \( n_{MRP}/\tau_{MRP} \approx n_{LMXB}/\tau_{LMXB} \) at this epoch. As illustrated by the case shown in Figure 1d, such a situation is quite possible for realistic values of evolutionary timescales. We have demonstrated in Figures 1b and 1c that it is also possible to have situations in which \( n_{MRP}/\tau_{MRP} \) is considerably larger than \( n_{LMXB}/\tau_{LMXB} \) in the present epoch for plausible values of evolutionary timescales.

In relating the observational situation to the basic theoretical expectations for the number ratio, \( N_n \), and rate ratio, \( R_n \), of evolving LMXB and MRP populations, we first emphasize that \( n_{MRP}/\tau_{MRP} \) and \( n_{LMXB}/\tau_{LMXB} \) are really the instantaneous rates of decay of the MRP and LMXB populations, respectively (see eqs. [2] and [3]), and not their “birthrates,” as they have been often called in previous discussions. Only under the assumption of a steady state can we equate them to the respective birthrates and to each other. For evolving populations, \( R_n \approx 1 \) is expected only under the circumstances described in the last paragraph. Thus, there is no basis for expecting \( n_{MRP}/\tau_{MRP} = n_{LMXB}/\tau_{LMXB} \) in general, and a deviation from equality does not, by itself, imply a serious problem. Indeed, since the observable quantities are really \( n_{MRP} \) and \( n_{LMXB} \), the actual test of agreement is as follows: given a plausible choice of \( \tau_{PSNB} \), \( \tau_{LMXB} \), and \( \tau_{MRP} \), does the calculated number ratio \( N_n \) at \( z = 0 \) at the present epoch agree with the observation, and, furthermore, does the calculated rate ratio \( R_n \) at the same epoch agree with that obtained from the observed \( N_n \) with this particular choice of timescales?

With the discovery of many more MRPs since the original KN work, the observational situation has changed somewhat. KN estimated \( N_n \) to be \( \sim 10^2 \) and \( R_n \) to be \( \sim 10 \) for the whole population and \( \sim 100 \) for short-period systems. The most recent estimate by L95 (using \( \times 5 \) times as many MRPs as KN) suggests \( N_n \approx 400 \) and \( R_n \approx 8 \) for both the whole population and \( R_n \approx 8 \) for short-period systems. From the case in Figure 1a, it is clear that the values of \( N_n \) and \( R_n \) typically discussed for the whole population are naturally obtained in the above picture with canonical timescales for the whole population. If short-period systems with longer \( \tau_{LMXB} \) (KN; CP) are considered alone, Figure 1b shows that \( R_n > 1 \) also occurs naturally, but with typical \( R_n \) values \( \approx 3 \). It is not clear how significant the discrepancy for short-period LMXBs is until a more detailed population synthesis has been undertaken. If further work confirms the discrepancy, we may conclude that either (i) a one-to-one evolution from PSNB to LMXB to MRP does not always occur: in certain parts of the parameter space, PSNBs do not evolve into the LMXB phase but ultimately produce MRPs (KW98), (ii) some potential LMXBs are rapidly destroyed, possibly by evaporation of the secondary (CP; T91), or (iii) there is a serious undersampling of the LMXB population because the majority is not X-ray active (L95).

4. AN OBSERVATIONAL TEST

We have demonstrated the inadequacy of steady state arguments in discussions of the LMXB-MRP birthrate problem for evolving populations with a time-variable SFR that peaks at a redshift \( \approx 1.5 \). We find that an evolutionary scheme can easily account for the observed MRP/LMXB number ratios, i.e., \( R_n \approx 1 \) for the overall population and larger \( R_n \) values for short-period LMXB systems. A closely related point is the relative behavior of high-mass X-ray binary (HMXB) and LMXB populations in a universe with a time-dependent cosmic SFR. HMXBs and LMXBs originating from stars formed in the same epoch have very different evolutionary timescales, since, although the initial evolution of both involves the evolution of a massive star to a supernova and the formation of a neutron star, LMXBs turn on as X-ray sources much later than HMXBs, only after the low-mass companion comes into Roche lobe contact, predominantly because of orbital decay by gravitational radiation and magnetic braking (KW98 and references therein). The relevant time lag is essentially the timescale \( \tau_{PSNB} \) introduced in § 2. Since the postsupernova evolution into HMXBs takes a negligibly short time on this scale, the global HMXB population will peak roughly where the number of stars (equal to the integral of the SFR) does. Thus, the global LMXB population will peak in redshift well after the HMXB peak. The combined X-ray binary activity of the two populations is expected to have a broad peak, or possibly a double peak, in \( z \), depending on the lag and the relative population sizes.

The dominant source of X-ray emission from normal spiral galaxies (i.e., those without an active nucleus) appears to be the integrated emission from their X-ray binaries (see Fabbiano 1995 and references therein), based on observations of nearby galaxies such as M31 (where individual sources can be resolved) and a comparison with the distribution in our Galaxy. These integrated X-ray luminosities are in the range \( L_x \sim 10^{34} - 10^{35} \) ergs s\(^{-1}\) and scale linearly with the blue-band luminosities of the galaxies. In our Galaxy, LMXBs dominate the total X-ray output, and this is also the same for M31, where the brightest sources are clustered around the bulge. For other relatively nearby galaxies, the average X-ray temperatures are in the range 3–6 keV, which is also consistent with a population of LMXBs (Kim, Fabbiano, & Trinchieri 1992). HMXB systems are also a significant component in some galaxies. They
dominate the 1–10 keV output of the irregular LMC and SMC galaxies. The X-ray outputs of starburst galaxies in the 1–10 keV band seem to be dominated by those of their HMXB populations and/or young supernova remnants (SNRs; Della Ceca, Griffiths, & Heckman 1997).

Our work demonstrates that the peak in the SFR at \( z \approx 1.5 \) will cause the integrated X-ray luminosity of galaxies in the redshift range 0.5–1.0 to be at least an order of magnitude higher than it is today. If the current understanding of LMXB evolution is correct, then a twin-peak signature of the dual LMXB and HMXB-SNR population is expected. This is caused by the delayed turn-on of the LMXB population relative to the short-lived and instantaneous turn-on of the HMXBs and SNRs associated with the peak in the SFR (Fig. 1). This second LMXB peak is in the redshift range 0.5–1.0 and is caused by the delay of the secondary in the PSNB to come into contact with its Roche lobe. The details of this signature (e.g., peak separation) can then be used to confirm the general picture as to the origin of LMXBs and to constrain models for their evolution. The expected flux levels \( (\sim 10^{-15} - 10^{-16} \text{ ergs cm}^{-2} \text{s}^{-1}) \) for this redshift range will be within the capabilities of AXAF, provided sufficient observing time \( (\sim 10^5 - 10^6 \text{ s}) \) is dedicated to a suitable field. These future observations will provide an important new diagnostic for understanding the evolution of X-ray binaries and the resulting MRP population.

It is a pleasure to thank V. Kalogera for communicating the results of her evolutionary calculations in advance of publication and P. Madau for supplying the MVP approximation.

REFERENCES

Bhattacharya, D. 1995, in X-Ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), 233
Camilo, F., Thorsett, S. E., & Kulkarni, S. R. 1994, ApJ, 421, L15
Côté, J., & Pylyser, E. H. P. 1989, A&A, 218, 131 (CP)
Della Ceca, R., Griffiths, R. E., & Heckman, T. M. 1997, ApJ, 485, 581
Fabbiano, G. 1995, in X-Ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), 390
Kalogera, V., & Webbink, R. F. 1996, ApJ, 458, 301
—. 1998, ApJ, 493, 351 (KW98)
Kim, D. W., Fabbiano, G., & Trinchieri, G. 1992, ApJ, 393, 134
Kulkarni, S., & Narayan, R. 1988, ApJ, 335, 755 (KN)
Lilly, S. J., Le Fèvre, O., Hammer, F., & Crampton, D. 1996, ApJ, 460, L1
Lorimer, D. R. 1995, MNRAS, 274, 300 (L95)
Madau, P., Della Valle, M., & Panagia, N. 1998a, MNRAS, submitted (MVP)
Madau, P., Ferguson, H. C., Dickinson, M. E., Giavalisco, M., Steidel, C. C., & Fruchter, A. 1996, MNRAS, 283, 1388
Madau, P., Pozzetti, L., & Dickinson, M. 1998b, ApJ, 498, 106 (MPD)
Tavani, M. 1991, ApJ, 366, L27 (T91)
Webbink, R. F., Rappaport, S., & Savonije, G. J. 1983, ApJ, 270, 678 (WRS)

Note added in proof.—It has recently been suggested (D. H. Hughes et al., Nature, 394, 241 [1998]; A. J. Barger et al., Nature, 394, 248 [1998]) from submillimeter studies that dust-enshrouded star formation in galaxies may be important in determining the SFR in the redshift range \( 2 < z < 4 \). If the peak in the SFR shifts to \( z \sim 2–3 \), as suggested by Hughes et al., the changes of detail in Figure 1 would be small. There is no qualitative change in the conclusions of this Letter, since they depend only on a sharp decline in the SFR in the recent past \( 0 < z < 1 \).