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AN EXPLANATION FOR METALLICITY EFFECTS ON X-RAY BINARY PROPERTIES

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ABSTRACT

We show that irradiation-induced stellar winds can explain two important metallicity effects in X-ray binaries: the higher numbers and softer spectra of X-ray binaries in metal-rich globular clusters (GCs) compared to those in metal-poor ones. As has been previously noted by Iben, Tutukov, and Fedorova, the winds should be stronger at lower metallicity because of less efficient line cooling. This speeds up the evolution of low-mass X-ray binaries (LMXBs) in metal-poor clusters and hence reduces their number. These winds can also provide extra material near the accreting object, which can create an intrinsic absorber that hardens the X-ray spectra of the metal-poor cluster systems relative to the metal-rich ones, as suggested by observations. We outline some additional observational predictions of this model.

Subject headings: binaries: close — galaxies: star clusters — globular clusters: general — stars: neutron — stars: winds, outflows — X-rays: binaries

1. INTRODUCTION

Globular clusters (GCs) are important laboratories for studying stellar populations, both main sequence and exotic. X-ray binaries are ~100 times overabundant in GCs compared to the field (see, e.g., the compilation of X-ray binary properties in Liu, van Paradijs, & van den Heuvel 2001) because of dynamical effects such as tidal capture and/or three- and four-body interactions (e.g., Clark 1975; Fabian, Pringle, & Rees 1975; Hills 1976). Furthermore, since detailed population studies of X-ray binaries require more sources than the ~100 in the Local Group, the extragalactic cases must be studied. Given that the ages and metallicities of individual extragalactic field stars are nearly impossible to determine, but that these properties can be inferred from the integrated light of GCs, the GC X-ray binaries in other galaxies represent an ideal place to study how age and metallicity affect X-ray binary populations.

Clearly, the dynamical properties of a GC are most important for predicting whether it has an X-ray binary (e.g., Pooley et al. 2003; Heinke et al. 2003). In addition, there is also a strong residual correlation between the number densities of X-ray binaries and the metallicities of the GCs. This was first suggested to be the case in the Local Group (Grindlay 1993; Bellazzini et al. 1995) and was shown more conclusively and dramatically in NGC 4472 (Kundu, Maccarone, & Zepf 2002, hereafter KMZ02). The possibility that this represents an age effect rather than a metallicity effect has been tested and found not to be the case using data on NGC 3115 and NGC 4365 (Kundu et al. 2003, hereafter K03). In NGC 3115, where the age spread is small but the metallicity spread is large, the metallicity effect was found to be at least as strong as that in other early-type galaxies. Conversely, in NGC 4365, where the age spread is large, the fraction of GCs with LMXBs does not vary much with age and is similar to that of older GCs with similar metallicities in other galaxies. It thus seems most likely that the LMXB population-enhancement effects first associated with the metallicity are in fact related directly to the metallicity and not to some other correlated property such as age, half-light radius, or distance from the center of the galaxy. It has also been noted that the metal-poor Large Magellanic Cloud (LMC) has a lower ratio of LMXBs to high-mass X-ray binaries (HMXBs) than the more metal-rich Milky Way (Cowley 1994; Iben, Tutukov, & Fedorova 1997, hereafter ITF97), which may be due to a combination of the metallicity effects and differences in their star formation histories.

An additional metallicity effect can be found in the differences between the soft X-ray spectra of these sources. It has been found that the spectra of the blue (i.e., metal-poor) GCs are harder than those of the red (i.e., metal-rich) GCs in the Milky Way, M31 (Irwin & Bregman 1999, hereafter IB99), and NGC 4472 (Maccarone, Kundu, & Zepf 2003, hereafter MKZ03). On the other hand, the quiescent LMXBs seem to show no evidence of a metallicity effect on the spectrum (e.g., Heinke et al. 2003), and the effect becomes much weaker or disappears at higher X-ray energies (Trinchieri et al. 1999; Di Stefano et al. 2002; Sidoli et al. 2001; MKZ03).

In this paper, we show that the current theoretical explanations for the overabundance effect are unlikely to match the typical factor of 3 difference between the probabilities of metal-poor and metal-rich GCs having LMXBs. We put forth a new scenario invoking the effects of irradiation-induced winds (IIWs) to explain the population difference. We also show that IIWs can explain the previously unexplained spectral difference effects as a result of the same physical process, with the same parameter values.

2. PAST THEORETICAL WORK

2.1. *Initial Mass Function Variations?*

Several attempts have been made to explain why metal-rich GCs have more LMXBs than metal-poor GCs, but as yet none seem satisfactory. Grindlay (1993) suggested that the correlation might be due to a flatter initial mass function (IMF) in higher metallicity GCs. The general consensus seems to be that the IMF is fairly universal (e.g., Kroupa 2002), and star formation theory suggests that any metallicity dependence is likely to be such that metal-rich stars have typically lower masses,

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since the Jeans mass is lower for metal-rich gas, which cools more efficiently (Larson 1998). Although the present day mass functions of metal-rich Galactic GCs are flatter than those of metal-poor Galactic GCs (McClure et al. 1986), this seems largely due to the fact that the metal-rich systems are located more centrally within the Milky Way and hence experience more extreme dynamical stripping of their low-mass stars, as seen observationally (Piotto & Zoccali 1999) and predicted theoretically (Vesperini & Heggie 1997; Baumgardt & Makino 2003).

2.2. *Effects of Stellar Radius*

Later, Bellazzini et al. (1995) suggested that the larger stellar radii of the stars in metal-rich GCs might contribute to the clusters' increased number densities of X-ray binaries. Larger stars should have a higher cross section for tidal captures and should overflow their Roche lobes at larger separations. The physics of tidal capture are a hotly contested issue, and some experts have suggested that tidal captures have great difficulty in forming systems similar to the X-ray binaries we observe (see e.g., Rasio & Shapiro 1991; Rasio, Pfahl, & Rappaport 2000 and references therein), while others have suggested that the majority of recycled pulsars may have been formed in tidal-capture systems (e.g., Di Stefano & Rappaport 1992). The alternative to the formation of X-ray binaries by tidal capture is formation through exchange interactions. These are most commonly three-body interactions in which a neutron star encounters a binary system composed of two noncompact stars and replaces one of those two stars, forming a binary system with the other (see, e.g., Clark 1975; Hills 1976), or four-body interactions, in which the neutron star is already in a binary system when it interacts with another binary system (see, e.g., Mikkola 1984; see also Fregeau et al. 2003 for a discussion of recent numerical work on three- and four-body interactions).

The easier Roche lobe overflow can be calculated using the standard assumption of a binary separation distribution that is logarithmic, i.e., $P(a) \propto 1/a$. Taking Kepler's law and the period-mass relation (eq. [4.9] of Frank, King, & Raine 1992, hereafter FKR92) we find that for a neutron star accretor and a typical (i.e., a 0.6 $M_{\odot}$) main-sequence GC star donor, the Roche lobe–overflow orbital separation is ~3 stellar radii and varies little with the donor star's mass. The separation at which Roche lobe overflow occurs increases linearly with the stellar radius for a fixed stellar mass. Given the logarithmic distribution of separations and a metallicity dependence of radius such that $R_* \propto Z^{1/8}$ (estimated from the stellar model interpolation formulae of Tout et al. 1996), the contribution of the term related to the increase in the number of Roche lobe–overflowing systems is $1 + \frac{1}{8}\log(Z_r/Z_p)/\log(r_{\max}/r_{\min})$, which is ~1.3 for a metallicity ratio of 10. Numerical calculations suggest that the tidal-capture rate goes as $R_*^{0.93}$ (e.g., Lee & Ostriker 1986), so the number of neutron star binaries formed by tidal capture goes as $Z^{0.12}$, which gives another factor of ~1.3 for a ratio of metallicities of 10. An additional small increase in the tidal-capture probability might come from the higher turnoff masses for the stars in metal-rich GCs (see, e.g., Chaboyer et al. 1996), but this factor should be no more than ~5%–10%. Stellar radius effects thus seem unlikely to make more than a ~60% difference (i.e., the product of the two 30% effects) in X-ray binary populations as a function of metallicity. In fact, since tidal captures are not likely to produce binary systems that are similar to the observed parameters, it seems more likely that the bulk of the LMXBs are formed in three- and four-body exchanges (see, e.g., Rasio et al. 2000), and so the overabundance factor in red clusters because of larger stellar radii is likely to be closer to a factor of 1.3 than 1.6.

3. THE IRRADIATION-INDUCED WIND MODEL

The mass donors in X-ray binaries can absorb and reprocess luminosities comparable to their intrinsic luminosities. The mass donor can then be "puffed up" to a larger radii (e.g., Tutukov & Yungelson 1980; Podsiadlowski 1991; Harpaz & Rappaport 1991), and the extra kinetic energy added to the envelope can drive off an evaporative wind with a velocity on the order of the escape velocity from the stellar surface (Arons 1973; Ruderman et al. 1989; Tavani & London 1993; Pfahl, Rappaport, & Podsiadlowski 2003). A fraction (~10%) of the gas lost by the mass donor is accreted by the compact star in much the same way as more typical stellar winds are accreted in HMXBs. The lifetimes of LMXBs are also accelerated by the extra mass loss caused by the IIWs (Tavani 1991a).

In addition to driving the evolution of the system, the IIW also leaves a large amount of gas in the environment of the X-ray binary. Most HMXBs show clear orbital modulations of the X-ray flux, especially at soft X-ray energies, and this is taken as evidence of internal absorption by the material in the stellar wind. An IIW from a low-mass star likely has a velocity much closer to the orbital velocities in the binary system, so the orbital modulation is not necessarily as strong as in the HMXBs. Still, the increased absorption has an effect on the spectrum.

Let us summarize a few key past results on IIWs. It is generally found that these winds should be more important in LMXBs than in HMXBs, since in LMXBs the amount of radiation absorbed by the mass donor from the accretion flow can far exceed the nuclear energy generation rate and can hence have a significant effect on the structure of the donor star (see, e.g., Tutukov & Yungelson 1980; Podsiadlowski 1991; ITF97); IIWs can affect HMXBs as well (see, e.g., Day & Stevens 1993) but have been much less well studied and are far less likely to dominate the overall mass transfer. Strong coronal winds are likely to result from IIWs and can be self-sustaining even if the mass donor does not fill its Roche lobe (see, e.g., Basko & Sunyaev 1973; Arons 1973); in fact, ITF97 have found that self-sustaining winds can produce large luminosities even if the mass donor fills only ~80% of its Roche lobe, in agreement with past results that a mass donor need not fill its Roche lobe if it is sufficiently irradiated (Tavani, Ruderman, & Shaham 1989). Some initial Roche lobe overflow is likely to be required in order to start accretion, but if the IIWs cause the mass loss to be substantially faster than what would be caused by orbital and stellar evolution, then the star might cease to fill its Roche lobe even as mass loss and accretion continue. Metal-rich stars can dissipate much of their absorbed energy through line cooling, while metal-poor stars dissipate this energy primarily through IIWs. Interpolating from the stellar cooling rate tables of Sutherland & Dopita (1993), the mass-loss rate due to the IIWs should scale as $Z^{-0.35}$; the system lifetime should scale as $Z^{0.35}$ if the mass loss is dominated by these winds and the lifetime is determined by the timescale for the mass donor to lose all its mass (ITF97).

As a caveat, we note that the treatment of ITF97 is based in part on the analytical irradiation treatment in Iben, Tutukov, & Yungelson (1995); while the results of this treatment agree well with the numerical work of Tavani & London (1993) within the parameter space of their models, ITF97 extrapolate outside this range. A more sophisticated numerical treatment may be in order for future work but is clearly outside the scope of this paper.

For a wind emitted at escape velocity from the mass donor, equation (4.35) of FKR92 shows that the fraction of the wind captured by the compact object is

$$\frac{\dot{M}}{-\dot{M}_w} = \frac{1}{4}\left(\frac{M_{\rm CO}}{M_d}\right)\left(\frac{R_d}{a}\right)^2, \tag{1}$$

where $\dot{M}$ is the mass accretion rate of the compact object, $\dot{M}_w$ is the wind mass-loss rate, $M_{\rm CO}$ is compact object's mass, M_d and R_d are the mass and radius of the donor star, respectively, and a is the orbital separation. Given typical values of $a = 4 \times 10^{11}$ cm, $R_d = 7 \times 10^{10}$ cm, $M_d = 0.6\ M_\odot$, and $M_{\rm CO} = 1.4\ M_\odot$, ~5% of the wind is accreted.

To simplify the calculation, we make the additional assumption that the red GCs accrete from a combination of Roche lobe overflow and IIWs while the bright LMXBs in blue GCs accrete from a self-sustaining wind. We later revisit this assumption and show that it is not necessary in order to reproduce roughly the observations. We now define the notation for the following five equations: $\dot{m}$ indicates the mass accretion rate onto the compact object, while $\dot{M}$ is the mass-loss rate. The subscript w indicates wind mass loss, RL indicates Roche lobe overflow effects, p indicates systems with metal-poor donors, r indicates systems with metal-rich donors, N indicates the number of systems, and Z indicates metallicity. Then

$$\dot{m} = \epsilon \dot{M}_w + \dot{M}_{\rm RL}, \tag{2}$$

where ϵ is the fraction of the mass lost in the wind that is accreted by the compact object, and is given by equation (1). Then, starting from the assumption outlined above that the Roche lobe overflow component is negligible for the metal-poor systems, we have

$$\dot{m}_p = \epsilon \dot{M}_{w,p}, \tag{3}$$

while for metal-rich stars

$$\dot{m}_r = \epsilon\left(\frac{Z_r}{Z_p}\right)\dot{M}_{w,p} + \dot{M}_{\rm RL}, \tag{4}$$

where $\dot{M}_{\rm RL}$ is the mass-loss rate due to the Roche lobe–overflowing component of the accretion flow and is assumed to be much smaller than the irradiation-driven mass-loss rate for the case of a metal-poor donor. Combining equations (3) and (4), we find that, for the same luminosity,

$$\frac{\dot{M}_r}{\dot{M}_p} = \left(\frac{Z_r}{Z_p}\right) + \epsilon - \epsilon\left(\frac{Z_r}{Z_p}\right)^{-0.35}. \tag{5}$$

The fraction of the mass loss in the metal-rich systems coming from the IIW is $(Z_r/Z_p)^{-0.35}$.

The number of X-ray binaries should scale as the formation rate times the lifetime. The formation rate effects have been studied by Bellazzini et al. (1995), and given their lines of argument we found in § 2.2 that the stellar radius effects should produce a difference of a factor of ~1.3 (if exchange interactions dominate) to 1.6 (if tidal captures dominate).

The effects of IIWs are predominantly on the system lifetimes. For systems at a given luminosity, equation (5) shows the difference in mass-loss rate, the inverse of which gives the ratio of source lifetimes. Thus, we find that

$$\frac{N_r}{N_p} = \frac{1}{(Z_r/Z_p)^{-0.35} + \epsilon - \epsilon(Z_r/Z_p)^{-0.35}}. \tag{6}$$

To compute the actual ratio of the number of red to the number of blue GC X-ray sources, it is necessary to multiply the factor of 1.3–1.6 from the stellar radius effects by the value from equation (6), which should be ~2.1 for the typical parameters $\epsilon = 0.05$ and $Z_r/Z_p = 10$. This gives a factor of between ~2.6 and 3.4, although this factor is probably a slight overestimate, because even the X-ray sources in the most metal-poor GCs are likely to have at least some Roche lobe overflow contribution to their X-ray luminosities.

It has been assumed that the stellar wind velocity is equal to the escape velocity from the surface of the star; this need not be the case. The extra wind energy of the metal-poor stars can be dissipated as a higher velocity wind rather than as a more dense wind. The fraction of the mass lost that is accreted scales as $v_{\rm wind}^{-4}$ (FKR92), which alternatively scales as the inverse of the wind power squared, for a constant mass-loss rate. The luminosity of the LMXBs in metal-poor GCs would then be suppressed by a factor of $\sim(Z_r/Z_p)^{0.70}$, while the lifetimes of the two classes of systems would be about the same. Because the luminosity function has a slope of about -0.55 (KMZ02), the ratio of the number of metal-rich to metal-poor cluster X-ray systems would then be $(Z_r/Z_p)^{0.39}$, which for the canonical factor of 10 difference between the two modes gives a factor of ~2.5 difference in the expected number of observed systems. We note that there might be systematic variations in the slope of the luminosity functions as a function of metallicity, but in the absence of measurements or a theoretical model, we assume they are the same.

We now wish to estimate the contribution of the IIW to the typically observed column density of these systems. We find an average density of mass in a sphere around the mass donor with radius equal to the diameter of the orbit. For a path length of the orbital radius, the column density $N_{\rm H}$ is then

$$N_{\rm H} = \frac{\dot{M}}{8 v_w r_{\rm orb} \mu}, \tag{7}$$

where μ is the mean molecular weight of the gas in the wind, v_w is the wind velocity, and $r_{\rm orb}$ is the orbital separation. This value, $\approx 6 \times 10^{21}$ cm^{-2}, should give a good approximation over orbital phase and inclination angle for the column density observed. Edge-on sources might be expected to have higher column densities, but the inclination angles for the GC LMXBs are not well constrained.

4. OBSERVATIONAL EVIDENCE FOR THE SCENARIO

4.1. *NGC 4472: Number of Sources*

NGC 4472 is the first galaxy for which the metal-rich mode was shown to have a higher fraction of GCs with LMXBs than the metal-poor mode (KMZ02). It seems unlikely that the GCs in NGC 4472 span a wide range of ages; they are all likely to be within a factor of 1.5–2 in age (Beasley et al. 2000; Cohen, Blakeslee, & Côté 2003). The metallicity effects on the number of GC X-ray sources are thus not likely due to an age difference between the metal-rich and metal-poor GCs. The age measurements are rather sensitive to the stellar population models for the Balmer lines, and there could still be a rather substantial age difference between the two samples. More strict constraints are the age measurements of Puzia et al. (2002), which confirm that the correlation between metallicity and LMXB-specific frequency in NGC 3115 is due to metallicity and not age (K03), but this system has fewer X-ray sources, so the ratio of the number of LMXBs in metal-rich and metal-poor clusters cannot be as well determined. Finally, there is the case of NGC 4365, where the ages do span a rather wide range but do not seem to be strongly correlated with the LMXB number density (K03).

The two modes in color for NGC 4472 peak at $V-I$ of 0.98 and 1.23 (KMZ02), corresponding to values of [Fe/H] of -1.26 and -0.08, respectively, according to the scaling law of Kundu & Whitmore (1998). Defining the metal-rich/metal-poor mode boundary to be $V-I = 1.10$, we find that 23 of the 450 metal-rich GCs and only 7 of the 370 metal-poor GCs contain X-ray sources. The metal-rich GCs are thus 2.7 ± 1.2 times as likely to contain X-ray sources as the metal-poor GCs.

4.2. *NGC 4472: Source Spectra*

The spectra also show a difference as a function of metallicity. While the individual spectra cannot be easily measured because of the low count rates, we have found that the summed spectra in NGC 4472 are harder in the blue GCs than in the red GCs (MKZ03). If we hold the neutral hydrogen column in both cases to the Galactic value of 1.6×10^{20} cm^{-2} and fit a power-law model to the data, we find a spectral index of 1.02 ± 0.27 for the blue GCs and 1.46 ± 0.10 for the red GCs (90% error contours). Allowing the column to float freely for the red GCs, we find $N_{\rm H}$ to be 4.8×10^{20} cm^{-2} and the power-law index to be 1.57. Then we fix the power-law index for the blue GCs and find that the data is best fitted with a column density of 1.1×10^{21} cm^{-2}.

We note that the solution to the spectral difference problem is not unique and is prone to numerous systematic uncertainties. The photoelectric absorption models we have used assume a solar composition for the absorbing medium and that the medium is cold (i.e., completely unionized). The underlying spectrum for accreting neutron stars and black holes in the 0.5–8 keV range is unlikely to be a single power law. Finally, we have averaged over many systems with different values of $N_{\rm H}$ and with different underlying spectra. Still, the rough information given, that the metal-poor GCs have an intrinsic absorption of $\sim 10^{21}$ cm^{-2} and that the column density is ~ 3 times as large for the metal-poor GCs as it is for the metal-rich GCs, seems to be a reasonable inference to draw from the data. The theoretical model predicts a higher value for the blue clusters, but the linear averaging tends to overestimate the effects on the spectrum, so the fact that our crude calculation overpredicts the amount of absorption is to be expected. Furthermore, the fact that the gas is likely to be partly ionized makes the fitted value of the $N_{\rm H}$ less than the actual value, and also some of the gas mass condenses into a geometrically thin accretion disk and hence has the effect of absorbing X-rays only if the inclination angle is very low. That the values are on the same order of magnitude and that the blue clusters have ~ 3 times as much absorption in the fits is about as good an agreement as can be expected given the crude modeling and the considerable theoretical uncertainties in the models of IIWs.

4.3. *Local Group Sources*

Both the Milky Way and the Magellanic Clouds have been rather well studied in terms of their X-ray stellar populations, and they show a metallicity difference on the same order as that between the metal-rich and metal-poor modes for GCs—about a factor of 10. As only a small fraction of the X-ray sources in any of these galaxies is in a GC, the star formation rate has a substantial effect on the relative number densities of X-ray binaries, so merely comparing number counts per unit stellar mass is not likely to prove fruitful. However, one can be fairly confident that the HMXB population is not heavily affected by IIWs because the luminosities of high-mass stars are much larger than the intercepted and absorbed luminosities. Therefore, the ratio of LMXBs to HMXBs might give a rough estimate of how important the IIWs are. The suggestion of ITF97 that the difference of this ratio might be indicative of IIWs playing an important role is therefore additional evidence in favor of this scenario.

5. POTENTIAL OBSERVATIONAL TESTS

This model makes several testable predictions. The first is that there should be a monotonic dependence between the number of LMXBs per unit of stellar mass and the metallicity; given enough statistics we should see a difference in the LMXB specific frequency as a function of the metallicity itself, and not just as a function of whether a cluster is in the metal-rich or metal-poor mode. Much new data has recently entered the *Chandra* archives, so it is now possible to test this prediction. There is already a correlation over a range of metallicities in the *ROSAT* spectral indices of GC X-ray sources that does not show a "critical metallicity" (IB99), so it seems our model passes this test so far.

This scenario also predicts that neutron star LMXBs are affected far more than other types of "dynamically interesting" sources. Blue stragglers and cataclysmic variables do not generate sufficiently high X-ray luminosities to excite substantial IIWs. Black hole systems, because of the higher mass compact objects, accrete the IIW gas much more efficiently.

IIWs have been suggested as an explanation of why systems such as 4U 1820$-$30 show a different period evolution than would be expected from conservative mass transfer driven by gravitational radiation (Tavani 1991b). An alternative is that the system is being affected by interactions with the GC potential (van der Klis et al. 1993). Gravitational wave observations from future missions, such as *LISA* (*Laser Interferometer Space Antenna*), may help break this degeneracy.

In addition, our scenario predicts that the metallicity effects should be essentially the same for field sources as they are for GC sources. Given two galaxies with similar star formation histories, the more metal-rich galaxy should have more field X-ray binaries. The natural way to test this hypothesis would be to look at the field X-ray binary populations of elliptical galaxies, as (1) they have very little recent star formation, and (2) metallicity tends to scale with galaxy mass. A potential problem with this approach is that a fraction (and indeed, perhaps a large fraction) of the field X-ray binaries may have been created through stellar interactions in GCs and released into the field through dynamical ejections or through tidal destruction of the GCs (see MKZ03 and references therein; see also Grindlay 1988). Given that both the tidal destruction rate and the metallicity are likely to be correlated with the mass, applying this test is not straightforward. On the other hand, the field sources of elliptical galaxies should show a metallicity effect on their energy spectra regardless of concerns over formation processes.

A better test might then be to extend the suggestion of ITF97 that the difference in the ratio of LMXBs to HMXBs in the Milky Way and the LMC is due to the metallicity difference. Since most HMXBs are accretion-powered pulsars, a reasonably good separation between the bright ends of the luminosity distributions of HMXBs and LMXBs should be possible, given good *Chandra* spectra of nearby spiral galaxies. We note that this is a generic prediction of any model in which the metallicity effects are strictly due to metallicity, but it provides a way to distinguish between true metallicity effects and effects of metallicity being correlated with parameters that are more difficult to measure, such as the dynamics of the system.

It has been suggested that past work on detailed spectral fitting on Milky Way GCs indicates that there is little evidence for intrinsic absorption in these systems (Sidoli et al. 2001). We note that this is not in conflict with our model. Sidoli et al (2001) did not obtain a satisfactory spectral fit to the data for M15, the most metal-poor of the Milky Way's GCs, with an X-ray source, probably because *BeppoSax* was not capable of resolving the two bright X-ray sources in the cluster (White & Angelini 2001). The other two most metal-poor clusters, NGC 1851 and NGC 6712, do show excess absorption in the X-ray compared with the optical, and the other GCs in the Milky Way all have optical extinctions significantly higher than the excess predicted by our model, so the fits would not be very sensitive to intrinsic absorption. In addition, we note that the fitting of Sidoli et al. (2001) was done using the standard assumption that the absorber would be cold material of solar composition. Since *BeppoSax* is sensitive to absorption edges in the ~few keV range, this might cause a systematic error in the fitted absorption value, as noted above. The results of Sidoli et al. (2001) certainly place upper limits on the amount of intrinsic absorption in the Milky Way's LMXBs, but these upper limits are mostly too high to place strong constraints on our model. A more sensitive test would come from *XMM-Newton* spectra of M31 GC X-ray sources, in which there would be little nonintrinsic absorption since the GCs are not viewed through the disk of the Galaxy. In fact, many of the M31 GC X-ray sources show evidence for intrinsic absorption, and the ones that do are predominantly in metal-poor clusters (Irwin & Bregman 1999).

In principle, differences in the luminosity functions between red and blue GC X-ray sources should also provide a way to discriminate between models of formation and evolution of their X-ray binaries. Unfortunately, it is difficult at this time to make a prediction from our scenario. It is not clear on theoretical grounds whether the extra wind energy in metal-poor systems manifests itself as a higher mass-loss rate, yielding probably slightly higher luminosities, albeit for much shorter amounts of time, or as higher wind velocities, in which case the efficiency of wind capture is lower, so the luminosity is lower at a given mass-loss rate, or as some combination of the two. Furthermore, there is not yet a sufficiently large sample of X-ray binaries in GCs to make a good comparison of the luminosity functions. This remains a good test to bear in mind for future work.

6. CONCLUSIONS

We have outlined a scenario whereby the two metallicity effects seen in LMXBs in GCs, higher number density in metal-rich clusters and harder low-energy X-ray spectra in metal-poor clusters, can be explained via the same mechanism: irradiation-induced stellar winds. We have presented additional feasible observational tests of this picture. While we have shown that the physics of the IIWs required to reproduce the observations is consistent with the most recent theoretical work, we also note that this is a rather complicated problem that is deserving of considerable additional attention by experts in binary stellar structure and evolution. We hope this paper helps to stimulate such work in the future.

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