Strong \([\text{O III}]\) and \([\text{N II}]\) emission lines in globular clusters from photoionized R Corona Borealis star winds

Thomas J. Maccarone\(^1\)\(^\star\) and Brian Warner\(^1,2\)

\(^1\)School of Physics and Astronomy, University of Southampton, Hampshire SO17 1BJ
\(^2\)Department of Astronomy, University of Cape Town, Cape Town, South Africa

Accepted 2010 October 26. Received 2010 October 25; in original form 2010 September 9

ABSTRACT
The globular cluster X-ray source CXO J033831.8−352604 in NGC 1399 has recently been found to show strong emission lines of \([\text{O III}]\) and \([\text{N II}]\) in its optical spectrum in addition to ultraluminous X-ray emission with a soft X-ray spectrum. It was further suggested that this system contained an intermediate-mass black hole which had tidally disrupted a white dwarf, producing the strong emission lines without detectable hydrogen emission. We show that an alternative exists which can explain the data more naturally in which the oxygen- and nitrogen-rich material is ejected from an R Corona Borealis (RCB) star. The scenario we propose here does not require an intermediate-mass black hole as the accretor, but also does not exclude the possibility.

Key words: stars: peculiar – stars: winds, outflows – X-rays: individual: CXO J033831.8−352604.

1 INTRODUCTION
The discovery of globular cluster X-ray sources in the Galaxy (e.g. Clark 1975) in the mid-1970s prompted the suggestion that X-ray emission might come from accretion on to intermediate-mass black holes (Bahcall & Ostriker 1975, hereafter BO75; Silk & Arons 1975, hereafter SA75). It has since been shown that all the bright Galactic X-ray sources are likely to have neutron star accretors – all but one of them show pulsations and/or surface thermonuclear runaways (Liu, van Paradijs & van den Heuvel 2007 and references therein; see also Altamirano et al. 2010). The other has been the subject of Doppler tomography which favours a neutron star accretor and rules out an intermediate-mass black hole accretor (van Zyl et al. 2004). The mechanism suggested by BO75 and SA75 is none the less still potentially relevant for extragalactic globular cluster X-ray sources, as well as for faint X-ray (Ho, Terashima & Okajima 2003) and radio (Maccarone 2004) sources in Galactic globular clusters. Recent work has suggested fueling of such black holes through tidal destruction of stars, which may be an effective way to provide more material in the vicinity of the black hole than standard stellar mass-loss provides (e.g. Rosswog, Ramirez-Ruiz & Hix 2009).

It has long been realized that the large globular cluster populations of nearby giant elliptical galaxies made them potentially rich targets for searching for globular cluster X-ray sources (Fabian, Pringle & Rees 1976). The \(\text{Einstein}\) observatory had the sensitivity and angular resolution to detect bright non-nuclear point sources in nearby galaxies, but only with the launch of \(\text{Chandra}\) has it been possible to localize such sources well enough to make reliable associations between the X-ray sources and globular clusters at distances beyond that of M 31. In recent years, several strong candidates for black holes in globular clusters have been identified (Maccarone et al. 2007, 2010; Brassington et al. 2010; Irwin et al. 2010; Shih et al. 2010). Two particularly interesting globular cluster X-ray sources show strong optical emission lines. The first, in NGC 4472, shows highly variable emission, peaking at about \(4 \times 10^{39} \text{erg s}^{-1}\), confirming that the bulk of the emission comes from a single X-ray source (Maccarone et al. 2007), and strong, broad \([\text{O III}]\) lines, with the lack of a clear detection of \(\text{H}\beta\) implying a ratio of oxygen to hydrogen much larger than that of solar composition material (Zepf et al. 2007, 2008; Steele et al. 2010). The second, CXO J033831.8−352604 in the Fornax cluster galaxy NGC 1399, is a bit fainter (\(L_X \approx 2 \times 10^{39} \text{erg s}^{-1}\)) and has not shown strong variability, but shows strong emission lines from both \([\text{O III}]\) and \([\text{N II}]\) – although these lines are substantially fainter and narrower than the lines seen from RZ 2109 (Irwin et al. 2010, hereafter I10). I10 argued that the properties of this source could be explained by tidal disruption of a white dwarf (WD) by an intermediate-mass black hole. In this Letter, we discuss a new interpretation for this system – that the globular cluster contains an R Corona Borealis (RCB) star, the wind of which is photoionized by the X-ray source.

2 DATA
We present no new data in this Letter, but do review the observational findings of I10 for the benefit of the reader. They report...
three X-ray observations with at least 100 counts, all showing an X-ray luminosity of $1.5 - 2.3 \times 10^{39}$ erg s$^{-1}$ and good spectral fits with models of power laws with $\Gamma$ in the 2.5-3.0 range, or disc blackbodies (Mitsuda et al. 1984) with $KT_{\text{in}}$ of 0.36-0.39 keV.

They made several optical spectra. They find emission lines of the [O m] $\lambda 5007$ doublet and the [N ii] $\lambda 6584$ Å doublet. They report half width at half maximum (HWHM) of the lines to be 70 km s$^{-1}$ and their plots show a peak flux density in [O m] $\lambda 5007$ Å of $1.7 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$ corresponding to a luminosity of about $2.0 \times 10^{35}$ erg s$^{-1}$, given the 70 km s$^{-1}$ HWHM, and in [N ii] $\lambda 6584$ Å of $2.0 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$, corresponding to a luminosity of about $2.5 \times 10^{35}$ erg s$^{-1}$. No other lines are found in this spectrum (Irwin, private communication). Visual inspection of their plots shows a noise level of about $3 \times 10^{-19}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$, so we can set as targets for photoionization calculations that the luminosity in the main peaks of [O m] and [N ii] are roughly similar, and both at about $2 \times 10^{35}$ erg s$^{-1}$, and that any other lines in the optical bandpass should be no more than about half the strength of those two lines.

3 THE PROBLEM WITH THE DISRUPTED WHITE DWARF SCENARIO

The key problem with the interpretation of I10, which they noted, but did not resolve, is that the nitrogen emission lines are stronger than the oxygen emission lines. Carbon–oxygen (CO) WDs rarely show nitrogen emission or absorption lines; in the process of producing a CO WD, the core nitrogen is usually consumed almost entirely in the helium-burning phase. Helium WDs can contain substantial nitrogen, but helium WDs are low-mass objects formed through a binary evolutionary pathway that causes the atmosphere of a low-mass evolved star to be ejected or transferred before the nuclear burning runs its course. As low-mass objects, extreme fine tuning of the impact parameter of their interactions with an intermediate-mass black hole is needed to allow them to be tidally disrupted, rather than to be tidally detonated (Rosswog et al. 2009). While no helium lines were found in the source spectrum, we show below that this is not a serious constraint on the amount of helium present, as there are plausible ranges for plasma temperature and ionization parameter for which helium can be the dominant species, but no helium lines will be detected.

4 AN ALTERNATIVE EXPLANATION: RCB STARS

There are three closely related classes of stars which are nearly hydrogen free and which have much larger ratios of nitrogen to oxygen than WDs do – RCB stars, extreme helium (EHe) stars and hydrogen-deficient carbon (HdC) stars (although we note that some authors consider the RCB stars to be a subclass of the HdC stars – e.g. Warner 1967). The prevailing formation mechanism for these classes is the merger of a He WD with a CO WD (e.g. Warner 1967; Webbink 1984; Clayton et al. 2007; Garcia-Hernandez et al. 2009), but there are alternative suggestions that single star evolution can produce a ‘final flash’ of helium burning (Iben, Tutukov & Yungelson 1996). Since the formation of RCB stars relies on a process related to close binary evolution, and the production of He WDs can be enhanced by stellar collisions, one might expect an overabundance of RCB stars and HdC stars in globular clusters, in the same way that X-ray binaries are overabundant in dense globular clusters compared with field star populations. There is some evidence that globular clusters contain substantial populations of stars with strongly enhanced carbon in their atmospheres (e.g. Strom & Strom 1971; Zinn 1973), but such studies are anecdotal at the present time. The abundance patterns in those stars are generally attributed to dredge-up, rather than mergers, but binary evolutionary processes may be necessary (e.g. Lucatello et al. 2005). We are not aware of any systematic search for RCB, EHe or HdC stars in globular clusters – although as discussed below in Section 4.3, some of the surveys for variable stars in globular clusters would have turned up some of the known RCB stars (see e.g. Clement et al. 2001).

4.1 Photoionization calculation

We use the xstar version 2.2 photoionization package (Kallman & Bautista 2001) to test whether feasible parameter values can yield reasonable emission-line spectra. We start from the assumption that an RCB star is located somewhere in the globular cluster core, and its wind is being photoionized by the bright X-ray source. There are many free parameters in play for a system of this kind, so we apply a trial-and-error approach to find a plausible set of parameters that reproduces the observed optical spectrum to within a factor of a few. Because many of the parameters are nearly degenerate with one another and, apart from upper limits we have only two constraints (since the ratio of the strengths of the lines within the doublets is fixed by atomic physics), we can state with near certainty that the parameter values here are not unique.

We start from the assumption that the photoionized gas will have chemical composition roughly similar to that of the RCB stars (see e.g. Garcia-Hernandez et al. 2009). We set the abundances in xstar for helium to four times the solar abundance, for carbon to 10 times the solar abundance, for nitrogen to 30 times the solar abundance and for oxygen to five times the solar abundance. We note that the study of Garcia-Hernandez allowed for a large range of oxygen and helium abundance but a small range for the other parameters. We leave out the lines from the heavier elements because they are relatively low in abundance and are not reported to have been seen, and because xstar calculations are sped up significantly by setting some abundances to zero. We set the temperature of the plasma to 7500 K (a typical temperature for warm RCB stars), the density to $10^4$ particles cm$^{-3}$, the ionizing source to a $4 \times 10^4$ K blackbody with luminosity $2 \times 10^{38}$ erg s$^{-1}$, the ionization parameter $\Xi$ to $10^{1.5}$ and the column density to $2 \times 10^{23}$ cm$^{-2}$. The emission in this model comes from a thin shell at a radius of $8 \times 10^{17}$ cm from the X-ray source. For this set of parameters, we find $L_{\text{6584}} = 2.6 \times 10^{35}$ erg s$^{-1}$, $L_{\text{5007}}$ is $1.1 \times 10^{35}$ erg s$^{-1}$, and the strongest optical line from a species not reported by I10 is the He i $\lambda 4686$ line, with $L = 4 \times 10^{37}$, well below the detection threshold in the spectra shown by I10. The calculations are thus in reasonably good agreement with the observed data, but the thinness of the shell, about $2 \times 10^{16}$ cm, is difficult to explain in a physically viable scenario.

We can alternatively consider the case where a stellar wind is being ionized. In this case, the wind is likely to subvert only a fraction of the solid angle seen from the accretor. xstar assumes spherical symmetry, so the calculation done will have to be a crude approximation of the realistic geometry. Larger column densities are necessary in this case, but also, the large column densities can exist without affecting the X-ray spectrum of the source, since the column need not be between the observer and the X-ray source. The region where $\delta R = R$ should contribute most strongly to the observed emission. The inner regions will have small solid angles contributing, and the outer regions will have low densities due to the
that it will be about $10^{17}$ to $10^{18}$ cm$^{-2}$. This calculation yields line luminosities of $5 \times 10^{35}$ and $3 \times 10^{35}$ erg s$^{-1}$, for the brighter lines of [N ii] and [O iii], respectively, after accounting for the fact that only about 10 per cent of the solid angle on the sky is emitting. We can then compute the mass-loss rate expected from the wind of an RCB star if its density is $400\,$cm$^{-3}$ at a distance $4 \times 10^{17}$ cm from the centre of the star, and find that it will be about $10^{-8} M_\odot$ per year, towards the upper end of the range observed from these objects. The gas should reach this radius on a timescale of a few thousand years, again, well within reasonable values for the lifetimes of these stars. Given that an acceptable solution has been found, and that the degeneracies allow other parameter values, it is clear that if RCB stars are abundant enough in globular clusters, it is plausible for the observed optical emission lines to come from photoionization of an RCB wind. We also note that the winds from RCB stars typically are $\sim 100$–$200$ km s$^{-1}$ in velocity (e.g. Clayton et al. 1994; Clayton, Geballe & Bianchi 2003), only slightly faster than the HWHM reported in I10.

The winds from RCB stars are probably driven by radiation pressure on dust (see e.g. Clayton et al. 2003), which then drags the gas along. This might then modify the expected photoionization signatures expected. We do not think this is a likely scenario, since we have assumed a temperature of 7500 K for the gas – a temperature at which the dust would be sublimated before travelling the approximate light-year out to the region in which the photoionized emission lines are produced.

### 4.2 The black hole mass of the photoionizing source

The implications for the mass of the black hole doing the photoionizing are weak. X-ray sources at luminosities of $2 \times 10^{39}$ erg s$^{-1}$ in the Milky Way are often found to be in the ‘very high’ spectral state, in which their spectra can be dominated by a $\Gamma \approx 2.7$ power law, in good agreement with the spectrum presented by I10. On the other hand, if one takes the best disc blackbody fit from I10, one finds that the inner disc radius should be about 1500 km, assuming a colour correction factor of about 3 (see e.g. Davis et al. 2005), and assuming the disc is observed face-on. This would correspond to a black hole of $\sim 100$–$1000 M_\odot$, depending on the inclination angle – the lower end of the range would imply a Schwarzschild black hole observed pole-on, while the upper end of the range would imply a Kerr black hole viewed close to edge-on. The upper end of the range is disfavoured by the fact that stellar mass black holes (Maccarone 2003) and active galactic nuclei (Ho 1999; Maccarone, Gallo & Fender 2003) tend to have hard power law spectra below a few percent of their Eddington luminosities. The soft X-ray spectrum is thus not a diagnostic of whether the accretor is of stellar or intermediate mass.

We also consider the possibility that the RCB star ejecta could be the mass supply to an intermediate-mass black hole, so that no additional bright X-ray source would need to be produced in the cluster. Gas within $GM/(v_\infty^2 + c_s^2)$ can be accreted on to the black hole, in a manner similar to Bondi accretion. This yields $R_{\text{acc}} = 10^{15}$ ($M/300 M_\odot$) cm. At that radius, the wind density will be $\sim 10\,$cm$^{-3}$ at this radius. The Bondi rate will then be $\sim 10^{14}$ g s$^{-1}$ – far too low to account for the observed X-ray luminosity, even before accounting for the fact that the Bondi rate seems to overestimate observed luminosities by factors of 10–100 (Perna et al. 2003; Pellegrini 2005).

### 4.3 Observable tests of the RCB hypothesis

A potential key diagnostic is the ratio of $^{18}$O to $^{16}$O. As predicted by Warner (1967), the HdC stars tend to have about two to three times as much $^{16}$O as $^{18}$O (Garcia-Hernandez et al. 2009). Most of the RCB stars show three to 20 times as much $^{16}$O as $^{18}$O (Clayton et al. 2007; Garcia-Hernandez et al. 2009) – still well above the solar value (e.g. Collier et al. 1998). Oxygen isotopic abundances in stars are usually measured from molecular bands, but this is not possible for the case of CXO J033831.8–352604. It is unlikely that the isotopic shift will be measurable in the 5007 line itself, especially if $^{16}$O is the dominant species, and merely not as dominant as it normally is. We were not able to find any calculations in the literature for the magnitude of the isotopic shift for [O iii]. 5007, but were able to find that the shift between $^{12}$B iii and $^{18}$B iii is about one part in 50000 (Litzen & Kling 1998). The fractional mass difference for $^{18}$O versus $^{16}$O is slightly larger, but the B iii transition takes place closer to the nucleus. The magnitude of the wavelength shift is likely to be too small to see for the [O iii] 5007 given the broadening of $70\,$km s$^{-1}$ reported by I10, but without a careful calculation of the wavelength shift expected for the isotopic difference, it is not clear whether a precise centroiding of the [O iii] might be useful – the centroiding of the line in I10 is likely to be accurate to only about $5\,$km s$^{-1}$ – probably larger than the isotopic shift, especially after weighting by the expected $^{18}$O/$^{16}$O.

A few other strong lines are expected, based on our xstar simulations, but outside the optical bandpass used by I10. The strongest line should be the 26-$\mu$m [O iv] line, and the strongest line observable with a ground-based CCD should be the 10830-Å line of He i, which should have a flux about 10 times lower than those of the stronger components of the [O iii] and [N ii] doublets (but only a factor of about 2 weaker than the [O iii] 30495 Å line). The [N iii] line at 57 $\mu$m is one of the strongest lines from the source – just weaker than [N ii], and just stronger than [O iii], but just falls within the bandpass of Herschel, and is about 1000 times too weak for Herschel to detect. A strong O vii line at 22 Å should also be present, but again, will have a line luminosity well below the detection thresholds for existing instruments in the X-rays. It thus may be possible, with very long integrations, to detect He i, but the main prediction of the model is that other spectral lines will be very hard to detect.

The idea has an alternative possible test – whether there is a sufficiently large population of RCB stars in the Galactic globular cluster population. It has been estimated that the total Galactic population of RCB stars is about 3200 by scaling up the much better constrained Large Magellanic Cloud (LMC) population size by the ratio of stellar masses (Alcock et al. 2001). Since only about 0.1 per cent of the Galactic stellar mass is in globular clusters, one would then find that there should be only a few RCB stars in the entire Galactic globular cluster population. However, if the double degenerate scenario for producing these stars is the correct one, then one should expect a substantial dynamical enhancement in the number of RCB stars in globular clusters relative to field star populations. Using the canonical factor of 100 that applies to X-ray binaries, a substantial fraction of the stars in globular clusters that appear to be on the asymptotic giant branch (AGB) should actually be RCB stars. The recent finding that RCB stars separate themselves from standard AGB star populations very well in the mid-infrared (Tisserand et al. 2010), due to increased dust re-emission, should make searches for them in the cores of globular clusters feasible in the near future using ground-based systems at 10 $\mu$m. On the other hand, even a dynamical enhancement of a factor of a few in the fraction of cluster stars that are RCB stars relative to the same fraction for the field
would probably be enough to make our scenario plausible – the ‘extra’ RCB stars should be concentrated in cluster cores where the bulk of stellar interactions take place, and should additionally be concentrated in the most massive clusters, since these tend to have the highest stellar interaction rates (e.g. Smits et al. 2006). In the context of our proposed scenario, it will be possible to make an estimate of the dynamical enhancement of RCB stars in globular clusters once a large number of spectra of globular clusters with bright X-ray sources have been published. At the present time, the sample of such objects is small, and possibly biased towards the clusters with emission lines.

We do note that there have been surveys for variable stars in globular clusters, and that some of these surveys have been made over time baselines of a decade or more (e.g. Sawyer Hogg 1980; Clement et al. 2001). These surveys make it clear that there is not a large population of RCB stars which fade as frequently as the RCB stars which have been discovered to date. Given the diversity of RCB stars in terms of how frequently they show fading events, however, it is not clear whether there is a sizeable population of RCB stars whose fading events are infrequent enough to have been missed so far. There are RCB stars which have shown only one fading event over long durations (e.g. XX Cam – one in over 100 yr; UV Cas – one in over 70 yr and Y Mus – one in over 40 yr – see Jurcsik 1996), suggesting that there may very well be some which show very infrequent fading events, and that the typical time-scales on which fading events happen for the well-known RCB stars are significant underestimates of the typical intervals between fading events for the population of RCB stars as a whole. Additionally, the optical gravitational lensing experiment (OGLE) light curves of known RCB stars often vary by a 10th of a magnitude or less over extended periods between fading events (e.g. Tisserand et al. 2010), which could lead to misclassification as non-variable stars or irregular/long-period variables in past surveys of globular clusters for variable stars.

Regardless of all, the scenario we propose does not require an overabundance of RCB stars in globular clusters of the same factor of 100 found for X-ray binaries. In fact, if the overabundance were that large, we would expect to find spectral lines like those reported by I10 in a very large fraction of globular clusters with bright X-ray sources have been published. At the present time, the sample of such objects is small, and possibly biased towards the clusters with emission lines.

5 CONCLUSIONS

We have shown that the combination of strong nitrogen and oxygen emission lines from CXO J033831.8—352604, coupled with a lack of hydrogen and helium emission lines can be well explained if the cluster contains a bright X-ray source near its centre photoionizing the wind of an RCB star. The scenario makes no requirements on the mass of the central black hole, and the past X-ray spectral information is inconclusive on this point – thus the case for an intermediate-mass black hole previously made is substantially weakened by this new possibility. If the scenario proposed here is correct, then it is highly likely that the formation rate of RCB stars in globular clusters is at least moderately dynamically enhanced.

ACKNOWLEDGMENTS

TJM thanks the European Union for support under FP7 grant 215212: Black Hole Universe. We thank the referee Geoffrey Clayton for a constructive and helpful report which improved the quality of the paper, and Jimmy Irwin for sharing unpublished details about the spectrum of CXO J033831.8—352604. BW’s research is supported by the National Research Foundation of South Africa and the University of Cape Town.

REFERENCES

Alcock C. et al., 2001, ApJ, 554, 298
Altamirano D. et al., 2010, ApJ, 712, 58L
Bahcall J. N., Ostriker J. P., 1975, Nat, 256, 23
Brassington N. et al., 2010, ApJ, preprint (astro-ph/1003.3236)
Clark G. W., 1975, ApJ, 199, L143
Clayton G. C., Lawson W. A., Cottrell P. L., Whitney B. A., Stanford S. A., De Ruiter F., 1994, ApJ, 432, 785
Clayton G. C., Geballe T. R., Bianchi L., 2003, ApJ, 595, 412
Clayton G., Geballe T. R., Herwig F., Fryer C., Asplund M., 2007, ApJ, 662, 1220
Clement C. M. et al., 2001, AJ, 122, 2587
Collier M. R., Hamilton D. C., Glockler G., Ho G., Bochsler P., Bodmer R., Sheldon R., 1998, J. Geophys. Res., 103, 7
Davis S. W., Blaes O. M., Hubeny I., Turner N. J., 2005, ApJ, 621, 372
Fabian A. C., Pringle J. E., Rees M. J., 1976, Nat, 263, 311
Garcia-Hernandez D. A., Hinkle K. H., Lambert D. L., Eriksson K., 2009, ApJ, 696, 1733
Ho L. C., 1999, ApJ, 516, 672
Ho L. C., Terashima Y., Okajima T., 2003, ApJ, 587, L35
Iben I., Tutukov A. V., Yungelson L. R., 1996, ApJ, 475, 291
Irwin J. A., Brink T. G., Bregman J. N., Roberts T. P., 2010, ApJ, 712, L1 (Irwin10)
Jurcsik J., 1996, Acta Astron., 46, 325
Kallman T., Bautista M., 2001, ApJS, 133, 221
Litzen U., Kling R., 1998, J. Phys. B: Atomic Molecular Opt. Phys., 31, L933
Liu Q. Z., van Paradijs J., van den Heuvel E. P. J., 2007, A&A, 469, 807
Lucatello S., Tsangarides S., Beers T. C., Carretta E., Gratton R. G., Ryan S. G., 2005, ApJ, 625, 825
Maccarone T. J., 2004, MNRAS, 351, 1049
Maccarone T. J., 2005, MNRAS, 360, L30
Maccarone T. J., Gallo E., Fender R., 2003, MNRAS, 345, L19
Maccarone T. J., Kundu A., Zepf S. E., Rhode K. L., 2007, Nat, 445, 183
Maccarone T. J., Kundu A., Zepf S. E., Rhode K. L., 2010, MNRAS, doi:10.1111/j.1365-2966.2010.17547.x
Mitsuda K. et al., 1984, PASJ, 36, 741
Pellegrini S., 2005, ApJ, 624, 155
Perna R., Narayan R., Rybicki G., Stella L., Treves A., 2003, ApJ, 594, 936
Rosswog S., Ramirez-Ruiz E., Hix W. R., 2009, ApJ, 695, 404
Sawyer Hogg H., 1980, J. R. Astron. Soc. Canada, 74, 363
Shih I. C., Kundu A., Maccarone T. J., Zepf S. E., Joseph T. D., 2010, ApJ, 721, 323
Silk J., Arons J., 1975, ApJ, 200L, 131
Smits M., Maccarone T. J., Kundu A., Zepf S. E., 2006, A&A, 458, 477
Steele M. M., Zepf S. E., Kundu A., Maccarone T. J., Rhode K. L., Salzer J. J., 2010, ApJ, submitted
Strom S. E., Strom K. M., 1971, A&A, 14, 111
Tisserand et al., 2010, A&A, in press (arXiv:1007.0800)
van Zyl L., Charles P. A., Arribas S., Naylor T., Mediavilla E., Hellier C.,
2004, MNRAS, 350, 649
Warner B., 1967, MNRAS, 137, 119
Webbink R. F., 1984, ApJ, 277, 355
Zepf S. E., Maccarone T. J., Bergond G., Kundu A., Rhode K. L., Salzer J. J.,
2007, ApJ, 669, L69
Zepf S. E. et al., 2008, ApJ, 683, L139
Zinn R., 1973, A&A, 25, 409

This paper has been typeset from a \TeX\ file prepared by the author.