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ABSTRACT
We examine the proposal that the subset of neutron-star and black-hole X-ray binaries that form with Ap or Bp star companions will experience systemic angular-momentum losses due to magnetic braking, not otherwise operative with intermediate-mass companion stars. We suggest that for donor stars possessing the anomalously high magnetic fields associated with Ap and Bp stars, a magnetically coupled, irradiation-driven stellar wind can lead to substantial systemic loss of angular-momentum. Hence these systems, which would otherwise not be expected to experience ‘magnetic braking’, evolve to shorter orbital periods during mass transfer. In this paper we detail how such a magnetic braking scenario operates. We apply it to a specific astrophysics problem involving the formation of compact black-hole binaries with low-mass donor stars. At present, it is not understood how these systems form, given that low-mass companion stars are not likely to provide sufficient gravitational potential to unbind the envelope of the massive progenitor of the black hole during a prior “common-envelope” phase. On the other hand, intermediate-mass companions, such as Ap and Bp stars, could more readily eject the common envelope. However, in the absence of magnetic braking, such systems tend to evolve to long orbital periods. We show that, with the proposed magnetic braking properties afforded by Ap and Bp companions, such a scenario can lead to the formation of compact black-hole binaries with orbital periods, donor masses, lifetimes, and production rates that are in accord with the observations. In spite of these successes, our models reveal a significant discrepancy between the calculated effective temperatures and the observed spectral types of the donor stars. Finally, we show that this temperature discrepancy would still exist for other scenarios invoking initially intermediate-mass donor stars, and this presents a substantial unresolved mystery.

Key words: Binaries: close - Stars: magnetic fields - X-rays: binaries.

1 INTRODUCTION
Magnetic braking is a relatively poorly understood mechanism for angular momentum loss in single stars as well as compact binaries, but is often invoked as the driver of mass transfer in compact binaries such as cataclysmic variables and low-mass X-ray binaries (see, e.g., Verbunt & Zwaan 1983; Rappaport, Verbunt & Joss 1983; Spruit & Ritter 1983). Models of magnetic braking usually invoke two key components: a large-scale magnetic field and a stellar wind. When coupled together, the field provides a long lever-arm which makes the wind an efficient angular-momentum sink.

According to conventional thinking, braking via a magnetically constrained stellar wind is inoperative in stars with radiative envelopes, (see, e.g. Kawaler 1988) and thus is confined to stars with $M \lesssim 1.5 M_\odot$. However, a subclass of intermediate-mass stars (the Ap and Bp stars) possess substantial magnetic fields; herein we suggest that an irradiation-driven stellar wind combined with their magnetic fields would lead to significant magnetic braking in compact binaries containing such stars.

We apply this heretofore unutilized magnetic braking to the formation of compact black-hole X-ray binaries. These systems are not easy to account for within previous formation scenarios – yet they comprise about half of the well-studied black-hole X-ray binaries. Nine of the seventeen systems listed in Lee, Brown & Wijers (2002), Ritter & Kolb (2003) and Podsiadlowski, Rappaport & Han (2003) (hereafter PRH, and references therein) have orbital peri-
ods < 1 d and inferred donor masses $\lesssim 1 M_\odot$ (see also McClintock & Remillard 2006). The empirical estimates of Wierse (1996) and Romani (1998) suggest that the Galactic population of short-period black-hole binaries may number over 1000 systems.

The standard formation scenario for such compact black-hole binaries typically requires a low-mass donor to have ejected the envelope of its primordial binary companion – the massive black-hole progenitor – as it spirals inwards during a common-envelope phase (see, e.g. de Kool, van den Heuvel & Pyleve 1987, also PRH and references therein). The orbital period is reduced from years to days, and the core of the massive star continues to evolve toward collapse and the formation of the black hole in the system. However, it is not clear how the energy required to unbind the envelope of the black-hole progenitor can be provided by a secondary star with a mass of only $\lesssim 1.5 M_\odot$ (e.g. Podsiadlowski, Cannon & Rees 1995; Portegies Zwart, Verbunt & Ergma 1992; Kalo ger 1994; PRH; see the Appendix for a brief summary of this argument). In the conventional scenario, this problem cannot simply be resolved by assuming a more massive secondary. Donor stars with $M \gtrsim 1.5 M_\odot$ are not expected to evolve into the short-period population, as they are thought not to be subject to canonical magnetic braking; mass transfer from the less massive to the more massive component of the system tends to widen the orbit (a consequence of conservation of angular-momentum).

In addition to this energetics problem, standard assumptions about star formation also suggest a demographic difficulty – even if the envelope of the massive primary could be ejected by the spiral-in of a low-mass star, there are expected to be relatively few primordial binaries with such an extreme mass ratio as required in that standard picture (e.g. Garmany, Conti & Massar 1980; Fisher, Schröder & Smith 2003).

Hence, attempts to produce these low-mass black-hole binary systems have sometimes been exotic, postulating – for example – descent from a triple system (Eggleton & Verbunt 1985), that the companion and black hole both form from a Thorne-Zytkow object (Podsiadlowski, Cannon & Rees 1993), or as a result of runaway accretion in the merger of a neutron-star with a massive star (PRH). Such ideas have been considered since the ‘simple’ alternatives often have far-reaching consequences, e.g., modifying the energetics of common-envelope evolution by a large factor to allow a low-mass star to eject the envelope of the primary is unpalatable, whilst magnetic braking from intermediate-mass radiative stars is not otherwise expected.

For standard input physics, PRH concluded that “black-hole binaries with low-mass secondaries can only form with apparently unrealistic assumptions”, which is an unsatisfactory position for binary evolutionary theory. PRH demonstrated that for the expected range of common-envelope parameters, black-hole binaries are much more likely to form with intermediate-mass companions than low-mass companions. They also pointed out that to form the observed short-period population from these intermediate-mass systems, an additional angular-momentum loss mechanism, such as anomalous magnetic braking, would be required.

An elegant way to solve this problem of forming short-period black-hole binaries would be to find such an angular-momentum loss mechanism for intermediate-mass stars. Ideally it would operate only on a subset of the intermediate-mass donor population, such that the long-period and short-period black-hole binary populations can both be formed. This paper suggests a self-consistent and plausible way for initially intermediate-mass companions to lead to the low-mass companions currently observed, at both long and short orbital periods.

Though the bulk of intermediate-mass stars are not expected to undergo magnetic braking, a fraction of such stars are known to have anomalously strong magnetic fields, the so-called Ap and Bp stars (Mos 1983; Braithwaite & Spruit 2004) with surface field strengths ranging from 100 G to over 10,000 G. When such a magnetic field is combined with an irradiation-driven wind from the surface of the donor star, a plausible angular-momentum loss mechanism is obtained. This paper is motivated by the realisation that such a mechanism can act on a portion of the intermediate-mass progenitor population to produce the short-period low-mass binary companions to black holes. Only a small portion of the intermediate-mass donors are affected – those with anomalously high field strengths. As we will show in Section 3, the lifetimes of systems with high magnetic fields are significantly longer, since the initial high mass-transfer rate quickly reduces the mass of the donor stars, making them evolve as lower-mass stars with much longer evolutionary timescales. This increases the relative fraction of the short-period black-hole binary population.

We find that the proposed magnetic braking mechanism should function as anticipated, driving systems to short orbital periods and producing low-mass donors. However, we also find that low-mass donor stars which descended from intermediate-mass progenitors have rather higher temperatures than can be consistent with the spectral types observed for the donor stars in short-period black-hole X-ray binaries. If no reconciliation of this discrepancy is found, this result is itself potentially very illuminating, as it would apply to any formation channel which invokes primordially intermediate-mass donor stars. This would imply that neither our understanding of common-envelope ejection needs severe revision, or an “exotic” channel is responsible for the formation of short-period black-hole binaries.

In section 2 we assemble the relevant physics to quantify the proposed anomalous magnetic braking mechanism and investigate its properties. In Section 3 we demonstrate how this magnetic braking naturally produces the observed short-period black-hole binaries. Finally, we consider observational tests of the model and illustrate its successes and major shortcomings.

2 ASSUMPTIONS AND DERIVATIONS

Magnetic braking removes rotational angular-momentum from a star when its stellar wind remains coupled to the stellar magnetic field as it leaves the star (e.g. Weber & Davis 1967; Mostel & Spruit 1987; Kawaler 1988). We make the standard assumption that the wind corotates out to the magnetospheric radius, defined as the radius where the mag-
ngetic pressure and ram pressure are balanced, i.e.,
\[
\frac{1}{2} \rho v^2 \simeq \frac{B^2}{8\pi} - \frac{B_a^2 R_d^2}{8\pi r^6},
\]
where \(r\) is the radial distance from the centre of the star, \(\rho\) and \(v\) are the density and velocity of the stellar wind, respectively, \(B_a\) is the magnetic field strength at the surface of the star, and \(R_d\) is the radius of the donor star. Here we have assumed a dipolar magnetic field structure. We can then combine eq. (1) with the continuity of mass applied to the stellar wind-loss rate, \(\dot{M}_{\text{wind}}\):
\[
\dot{M}_{\text{wind}} = \rho v 4\pi r^2,
\]
and the assumption that the wind velocity at the surface of the star is of order the escape speed:
\[
v \simeq \sqrt{\frac{2GM_d}{R_d}},
\]
(3) where \(M_d\) is the mass of the donor star under consideration) to yield the magnetospheric radius:
\[
r_m \simeq B_a^{1/2} R_d^{13/8} \dot{M}_{\text{wind}}^{-1/4} (GM_d)^{-1/8}.
\]
(4) We note that assigning a velocity to the wind by assuming it is equal to the escape speed at the magnetosphere, rather than the surface of the star, recovers the expression due to Lamb, Pethick & Pines (1974). We have performed the derivations below using both versions of the magnetospheric radius, and the differences in outcome are minimal.

The rate of change of angular-momentum due to magnetic braking, \(J_{\text{MB}}\), is then:
\[
J_{\text{MB}} = -\Omega_d r_m^2 \dot{M}_{\text{wind}} = -\Omega_d B_a R_d^{13/4} \dot{M}_{\text{wind}}^{1/2} (GM_d)^{-1/4},
\]
where \(\Omega_d\) is the angular rotation frequency of the donor star, and we have substituted in the expression for \(r_m\) from eq. (4). We expect that \(\Omega_d = \Omega_{\text{orb}}\) for close binaries as they are likely to be tidally locked.

2.1 Estimate of the Required Wind-Loss Rate

Before proceeding, we first estimate what angular-momentum loss rate, \(\dot{J}_{\text{MB}}\), will prevent the mass transfer in the binary (from the lower-mass donor to the higher-mass black hole) from widening the orbit and, in fact, will allow for orbital shrinkage. To make a rough estimate of the effect of \(\dot{J}_{\text{MB}}\) on the orbital separation, we assume conservative mass transfer and, from angular-momentum conservation, obtain:
\[
\dot{J}_{\text{MB}} = \dot{J}_{\text{MB}} \frac{\dot{M}_{\text{RLOF}}}{M_d} \left(1 - \frac{M_d}{M_{\text{BH}}} \right),
\]
where \(\dot{M}_{\text{RLOF}}\) is the mass-loss rate from the donor star that is transferred to the black hole via Roche-lobe overflow, and \(a\) is the orbital separation. If we require that \(\dot{J}_{\text{MB}} < 0\), and solve for \(\dot{J}_{\text{MB}}\), neglecting the mass of the donor star compared to that of the black hole, we find:
\[
\dot{J}_{\text{MB}} \gtrsim \dot{M}_{\text{RLOF}} (GM_{\text{tot}} a)^{1/2},
\]
where \(M_{\text{tot}}\) is the total mass of the binary. When we combine this expression with the middle term in eq. (5) and assume that the donor star is corotating with the orbit, we find:
\[
\dot{M}_{\text{wind}} r_m^2 \gtrsim \dot{M}_{\text{RLOF}} a^2.
\]

If we now parameterise the orbital separation in terms of the donor star radius and the dimensionless Roche-lobe radius, \(a = R_d/r_L\), and use the magnetospheric radius from eq. (3), we find the requirement for \(\dot{M}_{\text{wind}}\):
\[
\dot{M}_{\text{wind}} \gtrsim \frac{\sqrt{GM_d}}{B_a R_d^{5/2} r_L^2} \dot{M}_{\text{RLOF}}.
\]
(9) For typical mass ratios of interest, \(r_L \simeq 1/3\), and a donor star mass-radius relation of approximately \(M_a \propto R_a^{4/5}\) (for CNO cycle homology), we have:
\[
\left( \frac{\dot{M}_{\text{wind}}}{M_\odot \text{yr}^{-1}} \right) \gtrsim 5 \times 10^{13} \left( \frac{M_*}{M_\odot} \right)^{-3/2} \left( \frac{\dot{M}_{\text{RLOF}}}{M_\odot \text{yr}^{-1}} \right)^{2/5},
\]
(10) where \(B_a\) is expressed in Gauss.

This yields an estimate of the required mass-loss rate in the magnetically coupled wind of \(\dot{M}_{\text{wind}} \sim 4 \times 10^{-10} M_\odot \text{yr}^{-1}\) for the illustrative parameters: \(B_a = 1000\) G, \(M_d = 5 M_\odot\), and \(\dot{M}_{\text{RLOF}} = 10^{-8} M_\odot \text{yr}^{-1}\). Though our computational work does not explicitly employ eq. (10), it helps illustrate the magnitude of an irradiation-driven wind that is required to significantly affect the evolution of binary systems.

2.2 Irradiation-Driven Winds

It has been suggested that a substantial stellar wind may be driven from the donor star in a compact binary by the flux of X-radiation that is produced by accretion onto the collapsed star (Ruderman et al. 1988; Tavani & London 1993). Using an even smaller wind-driving efficiency than suggested by Tavani & London, we will show that anomalous magnetic intermediate-mass donor stars in close binaries can be braked sufficiently to form short-period systems. We will also show that for the majority of donor stars, i.e., ones with relatively weak magnetic fields, magnetic braking via an irradiation-driven stellar wind is not strong enough to drive the systems to shorter periods. In this same context, we note that Iben, Tutukov & Yungelson (1993) and Iben, Tutukov & Fedorova (1997) have also suggested that an induced stellar wind could constitute an important difference between the evolution of cataclysmic variables and low-mass X-ray binaries. Iben, Tutukov & Fedorova further pointed out that a radiation-enhanced stellar wind should have an effect on the magnetic braking, but their calculations did not examine the consequence of this, and they confined themselves to the orbital angular-momentum carried away directly by the wind — i.e. the specific orbital angular-momentum of the donor star.

The stellar wind-loss rate is obtained by assuming that a fraction of the accretion luminosity is converted into the kinetic energy of a wind, such that the matter in the wind becomes marginally unbound (consistent with our assumptions about the wind velocity). This energy-balance argument gives:
\[
\dot{M}_{\text{wind}} = L_* f_0 f_a \frac{R_d}{GM_d}
\]
(11) where the total accretion luminosity \(L_*\) is multiplied by a geometric factor \(f_0\) to find the flux that intercepts the donor, and a wind-driving energy efficiency factor, \(f_a\). The X-ray
luminosity is taken as some fraction, $f_x$, of power produced by an accretion rate of $\dot{M}_{\text{RLOF}}$ before the last stable orbit around a non-rotating black hole:

$$L_x \simeq \left(1 - \frac{\sqrt{3}}{3}\right) f_x \dot{M}_{\text{RLOF}} c^2,$$

where $c$ is the speed of light, $f_x$ is a rest-mass to energy conversion factor of order unity, and the factor in brackets is the dimensionless energy lost by the innermost stable orbit, i.e., at three Schwarzschild radii. Finally, we find:

$$\dot{M}_{\text{wind}} = \frac{\psi R_d \dot{M}_{\text{RLOF}}}{GM_d},$$

where, for convenience, we have defined:

$$\psi = \left(1 - \frac{\sqrt{3}}{3}\right) f_x f_\Omega f_c c^2.$$

Initially we used a combined value for $\psi/c^2$ of $\sim 10^{-6}$, based on the assumptions that the wind-driving energy conversion efficiency $f_c \sim 10^{-3}$, the solid angle $f_\Omega \sim 10^{-2}$ and $f_x \sim 1$. Clearly all these individual values are subject to some uncertainty, but we believe that the assumed values of $\psi$ are on the conservative side; e.g. [Tavani & London 1994] calculated wind efficiencies $f_c$ between $10^{-3}$ and $10^{-1}$. We began by using their lowest calculated values for $f_c$, and then took $\psi$ to be one and two orders of magnitude lower (i.e., $\psi/c^2 = 10^{-6}$ and $10^{-8}$).

In the computational models we took into account the fact that the irradiation-induced stellar wind carries away the specific orbital angular-momentum of the donor star in addition to the braking effect it produces on the rotation of the donor. We find that the direct loss of orbital angular-momentum via the stellar wind is quite small, as might be expected from the fact that the Alfvén radius is much greater than the dimensions of the binary system.

### 2.3 Analytic Results for $\dot{M}_{\text{RLOF}}$

A more sophisticated estimate than eq. (10) for the irradiation-induced wind loss can now be assembled. In particular, we can form a closed set of equations, eliminate $\dot{M}_{\text{wind}}$, and compute the mass-transfer rate when the magnetic braking torque just prevents the orbital separation from increasing due to the effects of mass transfer. Beginning with eq. (8), we substitute for the wind-loss rate from eq. (13), and use Kepler’s 3rd law to obtain:

$$J_{\text{MB}} = -B \sqrt{\frac{\psi \dot{M}_{\text{RLOF}} \dot{M}_{\text{tot}}}{a^3}} \left(\frac{R_d}{GM_d}\right)^{1/4}.$$

The time derivative of the expression for the total angular-momentum of the binary,

$$J_{\text{sys}} = M_d M_{\text{BH}} \frac{G a}{\dot{M}_{\text{tot}}},$$

where $M_{\text{BH}}$ is the black hole mass, with the assumption of mass conservation (i.e., $\dot{M}_{\text{tot}} = 0$) and the constraint that $a = 0$ (i.e., we are seeking the condition where the binary becomes neither wider nor tighter) yields:

$$J_{\text{sys}} = \sqrt{\frac{G a}{\dot{M}_{\text{tot}}} (M_d - M_{\text{BH}})} \dot{M}_{\text{RLOF}}.$$

Thence we can equate eqs. (10) and (15) and solve for $\dot{M}_{\text{RLOF}}$. We again use the parameterisation that $a = R_d/r_L$ and define $q = M_d/M_{\text{BH}}$ to find:

$$\dot{M}_{\text{RLOF}} = \psi B_s^2 r_L^4 \sqrt{\frac{R_d^2}{G^2 M_d}} \left(\frac{q+1}{q-1}\right)^2.$$

Equation (18) illustrates the behaviour of this equation, again assuming $R_d \propto M_d^{1/3}$. Note that the solutions scale linearly with the overall wind-driving efficiency $\psi$, and go as the square of $B_s$.

### 2.4 Effects on the Canonical LMXB Population

Before applying this model to Ap-star donors – adding an irradiation-driven wind to their intrinsically high field strengths – we did a calculation to check that such
physics would not unreasonably distort the standard picture of low-mass X-ray binary (LMXB) evolution during the X-ray phase. These systems contain neutron-star accretors and low-mass donor stars, and they are typically assumed to evolve via `conventional' magnetic braking (Verbiest & Zwaan 1983; Rappaport, Verbunt & Joss 1983), where the magnetic field of the donor is presumably generated by dynamo action. Stellar dynamos are by no means precisely solved phenomena, but following Collier Cameron & Jiansi (1994) we assume that the dynamo of the donor star is saturated at the orbital periods we consider ( ≤ 1 d). Hence we use fixed stellar dipole field strengths of 300 and 500 G.

For this simple assumption we found a range of LMXB evolutionary sequences that qualitatively reproduced test calculations performed with the magnetic braking parameterisation of Rappaport, Verbunt & Joss (1983). For clarity, the systems subject to our new mechanism do not experience conventional magnetic braking, though we do include gravitational wave radiation. Figure 2 contrasts two of these binary sequences: the irradiation-driven braking is, for these assumptions, less strong than conventional magnetic braking, and – when combined with conventional magnetic braking – does not greatly affect the standard picture of LMXB evolution. Note that in this case we assumed ψ/c² = 10⁻⁶ – the largest value of our wind-driving parameter.

3 BLACK-HOLE BINARY POPULATIONS

For populations of both short-period and long-period black-hole binaries to be produced, their progenitors must somehow differ. Something must distinguish between those systems to be produced, their progenitors must some-

We use an updated version of Eggleton's stellar evolution code (e.g. Eggleton 1972; Pols et al. 1997) to evolve systems with initial donor stars of 3, 4, and 5 M⊙ orbiting a black hole of mass 7 M⊙ with an initial orbital period of one day. We use the RLOF rate from the previous time-step to calculate the magnitude of the irradiation-driven stellar wind (eq. 13), and from this the magnetospheric radius (eq. 14), and finally the angular-momentum loss (eq. 15) in the current timestep. Overall, this is equivalent to using eq. (13).

Figure 3 shows the outcomes of these evolutionary sequences for a range of stellar magnetic field strengths, and with a wind-driving parameter ψ/c² = 10⁻⁶. With these parameters, only systems with donor stars having B_d ≤ 300 G will evolve to wide orbits; for larger dipole B fields the systems will become compact during the mass-transfer phase.

In Fig. 3 all the systems begin RLOF with a high mass-transfer-rate plateau lasting ~ 1 – 100 Myr (only as long as 100 Myr for the 300 G stellar fields), at the end of which a maximum in the orbital period evolution is reached. Donor stars with only 300 G fields reach core hydrogen exhaustion after ~ 1 Gyr, and their orbital periods lengthen as they expand. The donor stars with stronger fields – having lost mass more rapidly – evolve more slowly, continue burning hydrogen in their cores out to > 10 Gyr, and are good candidates for short-period black-hole binaries. They have all dropped below 1 M⊙ by ~ 100 Myr after the onset of RLOF; likewise, they spend relatively little time above an orbital period of ~0.5 days, which agrees well with the orbital parameters in table 1 of Lee, Brown & Wijers (2002). At 1 Gyr, with periods of ~ 0.25 d and donor masses around 0.5 M⊙, the 1 kG models produce mass transfer rates of ~ 10⁻¹⁰ M⊙ yr⁻¹.

We note explicitly that these systems spend most of their evolution with low-mass donors and are most likely to be observed as low-mass systems.

We have also calculated a range of binary sequences for less efficient wind-driving energetics, specifically ψ/c² = 10⁻⁷ and 10⁻⁸. For these lower wind-driving efficiency factors, higher magnetic fields for the donor star are required to obtain results similar to those shown in Fig. 6 (see eq. 18). In particular, B_d must scale as ψ⁻¹/².

These sequences demonstrate that the anomalous magnetic braking scenario is able to produce short-period systems for reasonable magnetic field strengths and conservative assumptions about the irradiation driven stellar winds.

3.1 The Long and the Short: Population Statistics

In order for the proposed anomalous magnetic braking scenario to be viable for producing short period black-hole binaries, it should yield the correct ratio of long to short period systems. From the small proportion of A-stars that have anomalously high magnetic fields (around 5% – see, e.g. Landstreet 1982, Sharlin et al. 2002), we might expect the population of short-period black-hole binaries to be much smaller than that of long-period systems, whilst the observed populations are roughly equal in size. However, the systems driven to lower masses more quickly by magnetic braking will live longer than those which are not, and so an imbal-
For a nominal wind driving energy conversion efficiency $f_e = 10^{-3}$ (see text), we show the evolution of three different companion masses (columns: left to right 3, 4 and 5 $M_\odot$) for three different surface magnetic field strengths: 300 G (dashed), 1000 G (unbroken line), and 3000 G (dotted). For the lowest field strength, the orbital period finally increases; also higher magnetic fields result in higher initial mass-transfer rates, as expected (see eq. 18). The mass-transfer rates have been slightly smoothed for clarity.

A representative lifetime estimate for the short-period systems is several Gyr (the 1000 G curves in Fig. 3 all continue indicating mass transfer until 10 Gyr, so the lifetime depends on choosing a minimum mass-transfer rate cutoff). Systems with the same initial orbital period, but with zero magnetic field, live only 200–400 Myr (see Fig. 4). This ratio of lifetimes – demonstrated explicitly in Fig. 4 – is approximately the required factor of 20 (to compensate for the small fraction of Ap stars), and shows that our model is naturally consistent with the observed numbers.

We note that relaxing our simplifying assumption – that the magnetic field strength does not decrease as the donor is stripped of mass – should make the lifetimes of the short-period systems even longer, as in the present calculations the low-mass donor stars are still subject to significant magnetic braking. More detailed lifetime arguments are also likely to depend on how evolved the donors are at contact and hence on the post-common-envelope orbital periods.

Wary of these unknown details, we calculated a range of simple population distributions to examine the feasibility of matching the observations of these low-mass black-hole binaries. A detailed presentation of these results is not included but we can draw an important general conclusion. The period distribution does seem to be best matched by decreasing the surface magnetic field strength when the donor mass falls below $\sim 1 M_\odot$; such evolution of the initially strong Ap field is eminently reasonable. (We repeat, however, that for all of the results shown in Figs. 2–5, the magnetic field strength was held constant.)

We note that – though we expect the stellar surface field strength to decay – the onset of transient behaviour would naturally reduce the efficiency of this irradiation-driven braking mechanism. Equation (5) reveals that the torque is proportional to the square root of the wind mass loss, and hence (via eq. 13) to the square root of the mass accretion rate. Persistent accretion is thus more efficient at driving braking than phases of outburst and quiescence, which is an effect that should be considered in more detailed future investigations of this mechanism. We also acknowledge that, in systems where the accretion rate begins to exceed the Eddington limit, the irradiation efficiency (and hence $\psi$) will drop; however, since the mass transfer is itself driven by our braking mechanism, this effect is to some extent self-regulating and would not necessarily result in widening of the binary.
3.2 Transient Behaviour

We checked the consistency of our models for compact black-hole binaries for their potential behaviour as soft-X-ray transients via the familiar thermal-ionization disk instability (Cannizzo et al. 1982; King et al. 1996, van Paradijs 1996, Dubus et al. 2001; Lasota 2001). At each step in the binary evolution we calculated the susceptibility of the accretion disk to instability, either by computing the temperature that would be attained in the outer portions of the accretion disk due to X-ray irradiation (using eq. (8) in Rappaport, Podsiadlowski, & Pfahl 2005), or by determining a critical accretion rate using expressions due to King et al. (1997) and Dubus et al. (1999). Though these different criteria yield considerable freedom of outcome, we find that all the methods for determining transient behaviour can match the observations: they agree that systems with $P_{\text{orb}} \lesssim 0.5$ days and $M_\Delta \lesssim 1M_\odot$ are transient (provided the magnetic braking at that epoch is not implausibly strong).

Common to all the criteria for transient behaviour is the prediction that during the initial phase of mass transfer – as the donor approaches $\sim 1M_\odot$ – the systems will be persistent sources. These systems will be evolving rapidly and thus there may be too few of them to have been discovered. However, the model predicts that there is a class of black-hole binaries with intermediate-mass donors and orbital periods $\lesssim 1$ day that are steady X-ray emitters.

In light of the fact that the wind-driving mechanism becomes significantly less efficient in transient systems, we point out that at the periods where the systems are predicted to become transient the effective temperatures of the donors have dropped within the range where ‘normal’ magnetic braking operates, i.e. the stars are capable of driving their own winds.

3.3 Observational Test: CNO Abundances

As well as population arguments, we can use individual objects to test the proposed anomalous magnetic braking mechanism. Observations that show CNO-processed elements on the surface of XTE J1118+480 (Haswell et al. 2002; the system has a 4.1 hour orbital period) are strong evidence that the donor is the descendent of an intermediate-mass star. Under the assumption that only dynamo-driven magnetic braking occurs, Haswell et al. (2002) found that only a very small parameter space could have produced XTE J1118+480 with such a CNO-processing signature, with a donor star of initial mass 1.5 $M_\odot$. Our irradiation wind-driven magnetic braking model relaxes these constraints considerably.

Moreover, the far UV spectrum taken by Haswell et al. appears to lack emission in oxygen as well as carbon. This fact is explained most naturally if the progenitor was more massive than 1.5 $M_\odot$, such that the full CNO tricyle could have operated. As PRH suggested, progenitors with such large masses would require a new angular-momentum loss mechanism – such as the one proposed in this work.

3.4 Observational Test: Spectral Types

Figure 5 compares the results of our binary evolution calculations with unevolved, primordially low-mass donors in the $T_{\text{eff}} - P_{\text{orb}}$ plane, and marks the periods of the known compact black-hole X-ray binary systems. The companion stars in these latter binaries are observed to have cool spectral types (see, e.g. Casares 2005), where the donors are
listed as broadly mid-K type stars; Torres et al. (2004) discuss their spectral type determination for XTE J1118+480). This forms a strong constraint on intermediate-mass progenitor stars: donors which have been allowed to evolve by the onset of mass transfer tend to have effective temperatures higher than required at the known orbital periods (see Fig. 6). Note that the behaviour of the 4 M_⊙ donor in Fig. 5 contrasts strongly with that predicted for the donors in CVs, where more evolved donors produce later spectral types (see, e.g. Beuermann et al. 1998; Baraffe & Kolb 2000).

We stress that the crosses in Fig. 6 mark the hottest temperatures consistent with the observed spectral types. This difference between theory and observation is hard to reconcile even when approximate non-grey atmospheric corrections are applied to our models (see Chabrier & Baraffe 1997; Baraffe et al. 1998; Podsiadlowski, Han & Rappaport 2003). At best, we can force the models to approach the temperatures of primordially low-mass ZAMS stars by having the donors begin transferring mass to the black hole early on the main sequence. However, even these values of T_{\text{eff}} are still too high.

The conversion between spectral type and effective temperature is non-trivial and it may be possible for our coolest models – late-G type donors – to be mistaken for mid-K stars, but we consider it unlikely that such a conversion error alone could account for the wide discrepancy between the bulk of our models and the observations. However we note that Torres et al. (2004) find that the donor star contributed only \sim 55% of the light in their observations of XTE J1118+480 during quiescence and suggest that unambiguous determination of donor spectral types in such systems is challenging.

We did consider one potential mechanism by which the secondaries in these systems might appear cooler than our models predict. The companion in the black-hole binary GRO J1655-40 (Nova Scorpii 1994, V1033 Sco) is known to be polluted with several \alpha-process elements (for a detailed investigation, see Podsiadlowski et al. 2002); such pollution would be expected to increase the opacity of the affected layers. We investigated both ad-hoc opacity modifications for the surface layers and uniform composition changes. Although we managed to produce closer correspondence with the observations, we cannot claim that the improvements were very dramatic.

4 SUMMARY AND CONCLUSIONS

In this paper we have proposed that the subset of neutron-star and black-hole binaries that form with Ap or Bp star companions will experience systemic angular-momentum losses due to magnetic braking, not otherwise operative with intermediate-mass companion stars. We have quantified how a magnetically coupled, irradiation-driven stellar wind can lead to substantial loss of systemic angular-momentum. We have demonstrated with detailed binary stellar evolution calculations that the proposed magnetic braking scenario involving Ap/Bp donor stars is effective in allowing such systems to evolve to short orbital periods (P_{\text{orb}} \lesssim 10 \text{ hr}). In the absence of such magnetic braking, binaries where intermediate-mass donor stars transfer mass onto more massive black holes inevitably evolve to long orbital periods, i.e., P_{\text{orb}} \gtrsim 2 \text{ weeks}.

Our Ap/Bp magnetic braking scenario has been applied to a specific astrophysical problem, namely the formation and evolution of compact black-hole binaries with low-mass companion stars. A number of previous studies have encountered difficulties with explaining the formation of such systems (PRH and references within). This led PRH to consider some form of anomalous magnetic braking to prevent systems from evolving to long orbital periods. In this work, we have presented such a mechanism that requires no new physics – and, indeed, is a consequence of previously published mechanisms acting in close binaries.

One of the conceptual difficulties with the formation of short-period black-hole binaries is that a low-mass donor star seems incapable of ejecting the common envelope during the prior formation of the black hole (PRH and references within; see also the Appendix). More massive stars, including stars of intermediate mass (i.e., 3 – 5 M_⊙), would be more likely to be able to eject the common envelope. Even under favourable (or optimistic) conditions in which a low-mass donor might conceivably be able to eject the common-envelope of the black-hole progenitor, stellar demographics suggest that the formation of binary systems with mass ratios of around 20 is very uncommon (see, e.g. Garmany, Conti & Massa 1980).

On the other hand, intermediate-mass stars are not thought to be subject to magnetic braking. As mentioned above, such angular-momentum losses are required to prevent the system from evolving to longer, rather than shorter, orbital periods. We have applied our Ap/Bp magnetic braking scenario to this problem in order to solve the difficulties with both the common-envelope ejection and the angular-momentum loss mechanism.

We have calculated a sequence of binary evolution models that demonstrate the Ap/Bp magnetic braking model is successful at reproducing the short orbital periods and low donor masses observed for the compact black-hole binaries. Moreover, we have shown that, since these systems have a longer lifetime than the corresponding systems without magnetic braking, the relative populations of compact and wide black-hole binaries could be explained in spite of the small fraction of A/B stars that are of the Ap/Bp class. Our model also helps to explain the evidence for CNO-processed material seen at the surface of XTE J1118+480.

As demonstrated in Fig. 5, however, the effective temperatures of our model donor stars are significantly higher than for those of the observed donor stars. This seems to be a generic difficulty with any formation scenario that invokes primordially intermediate-mass donor stars, and is not specifically related to our suggested angular-momentum loss mechanism. Any new angular-momentum loss mechanism proposed to explain the formation of short-period black-hole binaries would have to account for the same mismatch in spectral types. Hence in developing our model, we may thus have established a substantial constraint on the broad set of formation scenarios which begin with intermediate-mass secondaries.

The problem results from the fact that even though the initially intermediate-mass star loses much of its mass fairly rapidly (driven by magnetic braking), the star is still somewhat evolved chemically (both in He and CNO abundance)
by the time its mass has been reduced to $\sim 1 M_\odot$. This
prevents the donor stars from achieving the cooler observed
values of $T_{\text{eff}}$. Even in the limit that the intermediate-mass
star could lose much of its mass within a few of its thermal
timescales, the subsequent evolution would not automati-
cally lead to the evolutionary state of the observed donor
stars, i.e., undermassive and underluminous for a given or-
bital period.

Even though the systems that we have generated have
donor stars with hotter effective temperatures than are ob-
served, our analysis predicts that such systems should exist
and could be discovered in the future. The signature would
be orbital periods between $\sim 5-15$ hours, donor-star masses
of $\sim 0.5 - 1 M_\odot$, and effective temperatures $5000-7000$ K. If
black-hole binaries with these higher effective temperatures
are not found, then this would imply that either the donor
stars are rarely, if ever, of the Ap/Bp variety, that the pro-
posed magnetic braking mechanism is not as efficient as we
have calculated, or that the Ap/Bp magnetic fields do not
persist as mass is lost from the star.

In a subsequent paper we plan to explore further sce-
narios for the formation and evolution of compact black-
hole binaries. These include (i) rapid mass loss of the
intermediate-mass secondary at the end of the common en-
velope phase; (ii) explosive common-envelope ejection (see,
Eggleton & Podsiadlowski 2003); (iii) formation of the
low-mass donors in situ from the remnants of a failed
common-envelope ejection; and (iv) evolutionary paths of
low-mass donors that lead to the system properties that are
observed.

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Magnetic Braking of Ap/Bp Stars

9
We refer the reader to the original paper for further details on the methodology and results. The key finding is that if the secondary's Roche lobe radius exceeds the orbital separation at the onset of common-envelope ejection, the secondary can be ejected from the system. The exact conditions under which this occurs depend on the masses of the stars involved and the efficiency of mass transfer. The authors also note that the efficiency of mass transfer can be affected by various factors, such as the presence of a magnetic field or the geometry of the system. Overall, the study provides valuable insights into the dynamics of binary systems and the formation of black holes.