ESTIMATING THE KINETIC LUMINOSITY FUNCTION OF JETS FROM GALACTIC X-RAY BINARIES

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ABSTRACT

By combining the recently derived X-ray luminosity function for Galactic X-ray binaries (XRBs) by Grimm, Gilfanov, and Sunyaev and the radio–X-ray–mass relation of accreting black holes found by Merloni, Heinz, and Di Matteo, we derive predictions for the radio luminosity function and radio flux distribution (log $N$/log $S$) for XRBs. Based on the interpretation that the radio–X-ray–mass relation is an expression of an underlying relation between jet power and nuclear radio luminosity, we derive the kinetic luminosity function for Galactic black hole jets, up to a normalization constant in jet power. We present estimates for this constant on the basis of known ratios of jet power to core flux for AGN jets and available limits for individual XRBs. We find that, if XRB jets do indeed fall on the same radio flux–kinetic power relation as AGN jets, the estimated mean kinetic luminosity of typical low/hard state jets is of the order of $W_{XRB} \sim 2 \times 10^{37}$ erg s$^{-1}$, with a total integrated power output of $W_{XRB} \sim 5.5 \times 10^{38}$ erg s$^{-1}$. We find that the power carried in transient jets should be of a magnitude comparable to that carried in low/hard state jets. Including neutron star systems increases this estimate to $W_{XRB,ns} \sim 9 \times 10^{38}$ erg s$^{-1}$. We estimate the total kinetic energy output from low/hard state jets over the history of the Galaxy to be $E_{XRB} \sim 7 \times 10^{56}$ ergs.

1. INTRODUCTION

X-ray binaries (XRBs) have long been thought of as classic examples of accretion flows with little or no complicated outflow physics standing in the way of understanding the dynamics of these systems. It was not until recently that jets and outflows were recognized as important ingredients in the process of accretion, even in XRBs. The reason for this late appreciation is the fact that black hole XRBs are less radio-loud than active galactic nuclei (AGNs) by about 4 orders of magnitude (Heinz & Sunyaev 2003).

Accreting neutron star binaries, which are now also known to regularly produce radio-emitting jets (Fender 2005), are yet another factor of 30 more radio-quiet than black hole XRBs (Fender & Kuulkers 2001; Migliari et al. 2003). This further reduction in radio flux has made quantitative analysis of neutron star jets so difficult that rather little is known about them at present. Therefore, we focus on the properties of jets from black hole XRBs throughout most of this paper and present an extension of our work in § 3.5 to neutron star XRBs.

In consequence, while XRBs are among the brightest X-ray sources in the sky, their radio output is rather weak. This and the fact that the number of Galactic XRBs is much smaller than the number of AGNs are to blame for the facts that very little information about the radio power from XRB jets exists and that the physical properties of these jets are even less well known that those of AGN jets (which by themselves still pose many questions as to their exact makeup and dynamics).

Two types of radio-loud jetlike outflows have been observed in black hole XRBs. Following transitions in the X-ray spectral state, one can often observe bright radio flares, which are optically thin and show a power-law temporal decay on day timescales. The radio emission can be resolved on subarcsecond scales and shows proper motion (Mirabel & Rodríguez 1994; Hjellming & Rupen 1995; Fender et al. 1999). These ejections can carry a large amount of power, but are relatively rare. The second kind of jetlike outflow is associated with the so-called low/hard state in black hole XRBs (see McClintock & Remillard [2005] for a thorough review of X-ray states in XRBs). These outflows show a flat, optically thick radio spectrum and typically do not show a temporal decay. Only two of these sources have been resolved, showing a collimated jet on milliarcsecond scales (Stirling et al. 2001; Dhawan et al. 2000; Fuchs et al. 2003). Consequently, these types of flows are referred to as “steady/compact jets,” and for the remainder of this paper, we are mostly concerned with these types of jets.

Steady, compact, flat-spectrum jets are observed in virtually every Galactic black hole XRB in the low/hard state that is accessible to radio instruments. Significant progress in our understanding of XRB jets has recently been made, when a relation between the radio luminosity from these steady, compact jets and the hard X-ray luminosity was discovered in low/hard state sources (Corbel et al. 2002; Gallo et al. 2003). This relation has since been found to extend from stellar mass black holes all the way up the black hole mass scale to AGN jets (Merloni et al. 2003; Falcke et al. 2004). In the remainder of this paper, we refer to this relation as the “fundamental plane” (FP) of black hole activity.

The FP relation expresses both the fact that the radio luminosity from compact jets is nonlinearly correlated with the X-ray flux, as had already been discovered in the case of XRBs, and the nonlinear dependence of radio flux on black hole mass. The latter is responsible for the fact that AGNs are so much more radio-loud than XRBs. These relations can be understood naturally if the physics underlying the jet formation (ultimately, strong gravity and MHD in the inner accretion flow) are invariant under changes in black hole mass (Heinz & Sunyaev 2003).

This scale invariance implies that a relation between the radio luminosity $L_r$ emitted by the jet and the kinetic jet power $W_{kin}$ is underlying the radio–X-ray–mass relation. For reasonable parameters,\textsuperscript{3} this relation takes the form $L_r \propto W_{kin}^{1.42-\alpha_{/3}}$, where

3 For an electron spectrum with power-law index $p = 2$ and proportionality between kinetic jet power and magnetic energy density, $W_{kin} \propto B^2$, i.e., for magnetically driven jets.
where, for convenience, we express the X-ray luminosity in terms of the Eddington luminosity $L_{\text{Edd}} = 1.3 \times 10^{38}$ ergs s$^{-1}$ of a 1 $M_\odot$ object: $L_X \equiv L_X / L_{\text{Edd}}$. Following the interpretation of Merloni et al. (2003) and Fender et al. (2004b), we assume below that the transition at $\dot{m}_{\text{crit}}$ is due to a state change as observed in XRBs, where low-luminosity sources switch into the low/hard state. In XRBs, which we are concerned with here, steady, flat-spectrum jets are closely associated with the low/hard state. The details of this transition are irrelevant; we simply use the associated X-ray luminosity as an upper bound on the luminosity function. For a fixed black hole mass $M = 10 M_\odot M_{10}$, this transition corresponds to a critical X-ray luminosity $L_{\text{crit}} = 10 M_{10} \dot{m}_{\text{crit}}$. Miyamoto et al. (1995) and Maccarone (2003) showed that the transition from high/soft to low/hard state actually occurs over a range of values for $\dot{m}_{\text{crit}}$ and that a hysteresis exists, with sources on the descending luminosity branch staying in the high/soft state longer (to lower luminosities) than ascending sources, which make the state transition from hard to soft at higher luminosities. Fender et al. (2004b) show how the properties of XRB jets correlate with the position of a source on this hysteresis track. We comment on the impact that the uncertainty in $\dot{m}_{\text{crit}}$ has on our results in §3.3.

Following Heinz & Sunyaev (2003), the radio luminosity $L_r$ of the flat-spectrum core of the jet is related to the jet power $P_{\text{jet}}$ by

$$W_{\text{jet}} = W_0 \left( \frac{L_r}{L_0} \right)^{1/[1.42-(\alpha_r/3)]}$$

where $\alpha_r \equiv -\partial \ln L_r / \partial \ln \nu \approx 0$ is the radio spectral index and is close to zero for the flat-spectrum sources under consideration. Henceforth, we use $\alpha_r = 0$ unless noted otherwise. The value of $W_0$ is currently not well known: it is the normalization of the kinetic jet power in relation to its radio luminosity. It is not well known because jet power is still a very difficult quantity to measure, even after four decades of research on jets. We attempt to estimate it below and carry it through the algebra as a parameter until then. Combining equations (1) and (3), we can now write

$$L_X = \left( \frac{W_{\text{jet}}}{W_0} \right)^{[1.42-(\alpha_r/3)]/0.6} M^{-0.78/0.6}$$

We use the X-ray luminosity function for the Milky Way XRBs provided by Grimm et al. (2002; see Fig. 12 in their original paper). Where appropriate, we provide estimates based both on the actual data they derived (numerically integrated) and parameterized using the power-law approximation $dN/dl = N_0 l^{-\beta}$, fitted by Grimm et al. (2002) to give

$$\frac{dN_{\text{XMBX}}}{dl_X} = 0.7l_X^{-1.6}$$

$$\frac{dN_{\text{NMBX}}}{dl_X} = 5l_X^{-1.4}$$

for $l_X < 1$ and on the actual data. The X-ray luminosity function does not show a low-luminosity cutoff. But at low luminosities the observed number of sources is very small due to the

Naively, $W_0$ can be taken as a radiative efficiency, although it should be kept in mind that most of the radiation is emitted at high frequencies; thus, the radiative efficiency is oftentimes not well defined, as the high-energy cutoff of individual sources is hard to measure and it is not clear which parts of the spectrum actually arise in the jet and which arise in the accretion flow.
sensitivity limits of the All-Sky Monitor on the Rossi X-Ray Timing Explorer (RXTE). However, a comparison with higher sensitivity (but smaller sky coverage) data of the Galactic Ridge Survey (Sugizaki et al. 2001) by the Advanced Satellite for Cosmology and Astrophysics (ASCA) shows that the XRLF does not require a cutoff down to \( \sim 10^{-3} \) ergs s\(^{-1}\) (Grimm et al. 2002).

The radio–X-ray correlation in XRBs has been observed down to X-ray luminosities of about \( L_x \sim 10^{41} \) in the case of GX 339–4. While there is reason to believe that the radio–X-ray relation might break down at very low luminosities (the synchrotron X-ray component from the jet scales more slowly with \( m_t^t \), than the X-rays from the accretion flow, \( F_{X,acc} \propto m_t^t \), Merloni et al. 2003; Heinz 2004; Yuan & Cui 2005), we take \( L_x,\min = 10^{-4} \) as a secure upper limit on the low-luminosity cutoff of the radio–X-ray relation.

The relative fraction of black holes as a function of \( l_x \) in both the low-mass X-ray binary (LMXB) and the high-mass X-ray binary (HMXB) luminosity functions is unknown. Thus, for lack of better knowledge, we use the ratio of observed black holes to neutron star XRBs, which is about 10%. We parameterize this unknown fraction as \( \zeta = (dN_{BH}/dN_X)/(dN_{NS}/dN_X) = 0.1 \zeta_{0.1} \) and assume that the fraction of black holes is constant as a function of \( l_x \). Given the uncertainty in these estimates and the lack of knowledge of the black hole mass function, we henceforth assume that the mean black hole mass is 10 \( M_\odot \), and evaluate all quantities for this black hole mass.

The instantaneous kinetic luminosity function for jets from Galactic black holes is then

\[
\frac{dN}{dW_{jet}} = \frac{1.42 - (\alpha_r/3)}{0.6W_0} M^{-0.78/0.6} \left( \frac{W_{jet}}{W_0} \right)^{0.82 - (\alpha_r/3)/0.6} \frac{dN}{dl_x}
\]

for \( l_{x,\min}^{0.42} W_0 M^{0.55} < W_{jet} < \zeta_{c}^{0.42} W_0 M^{0.55} \). For the power-law parameterizations, we have

\[
\frac{dN_{LMXB}}{dW_{jet}} \approx \left( \frac{W_{jet}}{W_0} \right)^{\alpha_r/3 - 2.42} M^{0.78/10} \frac{W_0}{\zeta_{0.1}}
\]

\[
\frac{dN_{LMXB}}{dW_{jet}} \approx 4 \left( \frac{W_{jet}}{W_0} \right)^{\alpha_r/3 - 1.95} M^{0.52/10} \frac{W_0}{\zeta_{0.1}}
\]

in the same bounds. All that is left to do is to determine \( W_0 \), clearly the most difficult and uncertain part of this exercise.

3. ESTIMATING THE ABSOLUTE KINETIC LUMINOSITY FUNCTION

3.1. Estimating \( W_0 \)

3.1.1. Estimates of the Kinetic Power in AGN Jets

Information on the kinetic power from XRB jets is just starting to become available. We discuss the available estimates and how they can be used to constrain \( W_0 \) in § 3.1.2. First, however, we consider the case of AGN jets, for which information about the kinetic power is readily available and undisputed in a number of important cases. There are three AGN jet sources in the sample used to derive the FP relation by Merloni et al. (2003) that have reliable estimates of the jet power: M87, Cyg A, and Per A. These estimates are derived from average powers on very large spatial scales in the cases of Cyg A and Per A, while for M87 power estimates exist both for large spatial scales from X-ray cavities and for jet scales (Bicknell & Begelman 1996).

We can use these sources to estimate \( W_0 \) (Heinz et al. 2005). We should keep in mind, though, that the sources each have some offset from the FP relation due to the intrinsic scatter around the plane. Furthermore, the large-scale power estimates are time averaged (over times much longer than the dynamical time of the central jet that is currently producing the radio emission) and might not be representative of the current jet power. However, the fact that the estimate we get from M87 alone (where the large-scale power estimate agrees with the smaller scale estimate) is consistent with the ones obtained from the other two sources indicates that we are probably not too far off. It should also be noted that all of these sources show compact, flat-spectrum jets, which is critical if we want to use them as templates for low/hard state jets from Galactic XRBs.

The rough power estimates for the three sources are \( W_{0,\text{M87}} \approx 10^{44.5} \) ergs s\(^{-1}\), \( 10^{44} \) ergs s\(^{-1}\), and \( 10^{44} \) ergs s\(^{-1}\) for Cyg A, M87, and Per A, respectively (Carilli & Barthel 1996; Bicknell & Begelman 1996; Forman et al. 2005; Fabian et al. 2002), while their core radio luminosities are \( 10^{41.4}, 10^{41.9} \), and \( 10^{41.7} \) ergs s\(^{-1}\), respectively. Thus, the normalization constants we derive for the sources are \( W_{0,\text{CygA}} \approx 6.3 \times 10^{37} \) ergs s\(^{-1}\), \( W_{0,\text{M87}} \approx 2 \times 10^{37} \) ergs s\(^{-1}\), and \( W_{0,\text{PerA}} \approx 2.6 \times 10^{36} \) ergs s\(^{-1}\), each carrying considerable uncertainty from the estimate of the kinetic power and from the fact that the sources scatter around the FP.

We can also calculate what the radio power would be if there were no scatter around the relation, by estimating the unbeamed radio flux from the X-ray luminosity and the mass of the objects, using the FP relation. In this case, the normalization constants are \( W_{0,\text{CygA}} \approx 10^{38} \) ergs s\(^{-1}\), \( W_{0,\text{M87}} \approx 6.3 \times 10^{37} \) ergs s\(^{-1}\), and \( W_{0,\text{PerA}} \approx 3.7 \times 10^{37} \) ergs s\(^{-1}\), which is significantly more homogeneous.

This expression is more appropriate to use in an average sense when considering a large sample of sources, since the radio emission probably carries the biggest fraction of the scatter in the FP relation due to variations in relativistic beaming, black hole spin, and spectral index. In this particular case it is also more appropriate because we are using the X-ray luminosity of XRBs and the FP to convert X-ray fluxes into radio fluxes. Thus, using X-ray fluxes to calibrate this method seems to us to be the most consistent approach. We therefore use this “corrected” estimate of the efficiency, which averages to

\[
W_0 \approx 6.2 \times 10^{37} \text{ ergs s}^{-1} \quad W_{37.8}
\]

with an order-of-magnitude uncertainty. We carry \( W_{37.8} \) through the rest of the paper to allow the reader to adjust for future improvements and different personal preferences in this value.

3.1.2. Limits from Power Estimates of XRB Jets

There is relatively little information about the kinetic power output of individual Galactic XRBs that we could use to calibrate \( W_0 \). The best information available to date is on the jet in Cyg X-1. The compact jet is resolved on scales of 15 mas, and using a simple Blandford-Koenigl model (Blandford & Koenigl 1979) to describe the radio emission, one can set a lower limit of \( W_{\text{jet}} > 3 \times 10^{33} \) ergs s\(^{-1}\), which is very likely much lower than the true kinetic power. For the radio flux of 12 mJy, this translates to a lower limit of \( W_0 > 10^{34} \) ergs s\(^{-1}\) (Stirling et al. 2001).

Based on the IR observations of compact jet in GRS 1915+105, Fender & Hendry (2000) argue that the normalization for the kinetic power must be larger than \( W_0 > 2 \times 10^{35} \) ergs s\(^{-1}\), since,
averaged over a sufficient timescale, the kinetic power must exceed the radiative output of the jet. Similar arguments are commonly used in the analysis of blazar emission (Ghisellini & Celotti 2001).

Detailed modeling of the spectral properties of the XTE J1118 jet has led Markoff et al. (2001) and Yuan & Cui (2005) to propose values of the kinetic power that translate to normalization values of \( W_0 \approx 10^{38} \) and \( 2 \times 10^{37} \) ergs s\(^{-1}\), respectively. It is important to note that the jet power in these models is essentially a free parameter, since parameters such as the proton content and the opening angle of the jets are unknown. Nonetheless, these estimates show that reasonable parameterizations used in the literature for a variety of models are consistent with the estimate we present in equation (10). Malzac et al. (2004) argue for a lower limit of \( W_0 \geq 2 \times 10^{38} \) ergs s\(^{-1}\) (higher but still consistent with our estimate in eq. [10] below) on the basis of their model for the timing behavior of the accretion flow. However, this model does not differentiate between a windlike outflow and a jet (as long as the flow acts as an energy sink), and it is not clear how this limit can be turned into a constraint on the jet power alone.

Calorimetric observations (i.e., radio lobes, X-ray cavities, and shocks surrounding the cocoons of radio sources) are the most reliable way to estimate jet powers. Recently, evidence for the interaction of the Cyg X-1 jet with its environment was discovered in the form of a ring of thermal emission that is probably the shock driven into the interstellar medium by a so-far undetected radio lobe around Cyg X-1 (Gallo 2005). The analysis of this shock indicates that the average jet power is \( 10^{36} \) ergs s\(^{-1}\) \( < (W) < 10^{37} \) ergs s\(^{-1}\). As we show in § 3.2, this corresponds to the range \( 5 \times 10^{36} \) ergs s\(^{-1}\) \( < W_0 < 5 \times 10^{37} \) ergs s\(^{-1}\), which is consistent with the estimate we present in equation (10).

While Cir X-1 does appear to possess a radio lobe, it does not seem to show a shock similar to that of Cyg X-1, and thus estimates of the source age are more difficult. Furthermore, it is still not entirely clear whether Cir X-1 is a neutron star or black hole. Heinz (2002) estimated the source power to be \( (W) \approx 10^{35} \) ergs s\(^{-1}\). This limit is consistent with that for Cyg X-1 if the system is in fact a neutron star rather than a black hole, in which case we would expect the average source power to be smaller by a factor about equal to the mass ratio, roughly by an order of magnitude.

Finally, Kaiser et al. (2004) estimate the mean kinetic power of the jets in GRS 1915+105 from the tentative association with what appear to be two Infrared Astronomical Satellite (IRAS) hot spots (Chaty et al. [2001]; note that this association leads to distance estimates that are marginally inconsistent with other measurements) to be \( 10^{36} \) ergs s\(^{-1}\) \( < (W) < 10^{37} \) ergs s\(^{-1}\). If a significant portion of the power in the GRS 1915+105 jet comes from the compact/steady flow, this estimate is consistent with the estimate above for Cyg X-1 and again implies that \( 5 \times 10^{36} \) ergs s\(^{-1}\) \( < W_0 < 5 \times 10^{37} \) ergs s\(^{-1}\); it is also very much in line with what we estimate below based on AGN jets.

3.2. The Absolute Kinetic Power Output of Galactic Black Holes in the Low/ Hard State

With the estimate of \( W_0 \) in hand, we can evaluate a number of important quantities. The first is simply the kinetic luminosity function for XRBs. The approximate analytic expression is given by equation (7) with the value of \( W_0 \) from equation (10). Using the actual data of the XRB luminosity function from Grimm et al. (2002), we can also plot the kinetic luminosity function, as shown in Figure 1.

The second is the total kinetic power released into the Galaxy by steady, flat-spectrum jets from XRBs. It is simply the integral over the luminosity function:

\[
W_{\text{tot}} = \int dW_{\text{jet}} \frac{dN}{dW_{\text{jet}}},
\]

\[
W_{\text{HMXB}} \approx 2 \times 10^{36} \text{ ergs s}^{-1} \times W_{37.5}^{0.55},
\]

\[
W_{\text{LMXB}} \approx 3.5 \times 10^{38} \text{ ergs s}^{-1} \times W_{37.5}^{0.55}.
\]

Note that the power output from HMXBs is dominated by low-luminosity sources; the total power estimate depends on the assumed lower cutoff and is thus a lower limit. For LMXBs, the total power is essentially a logarithmic function of the lower limit on \( W \) to lowest order; i.e., each decade in \( W_{\text{kin}} \) contributes the same amount of total power. At low luminosities, however, both the HMXB and the LMXB luminosity functions turn over, the radio–X-ray relation presumably breaks down, and the total number of XRBs is limited, so, as expected, the kinetic luminosity function does not diverge.

It is worth pointing out that the value for \( W_{\text{tot}} \) is somewhat larger than the estimated total energy output from low/hard state XRB jets presented in Heinz & Sunyaev (2002), which was derived from very different arguments (we should note that the estimate presented in this paper should be significantly more reliable). This also implies that the statements made in that paper about the total contribution from XRB jets to the Galactic cosmic radiation spectrum still hold (i.e., that the total contribution is small; however, spectrally unusual signatures such as narrow lines or Maxwellian features will stand out measurably).

Given the estimated star formation rate of \( 3 M_{\odot} \) yr\(^{-1}\) of the Galaxy, and the fact that the HMXB luminosity function is a good estimator of the star formation rate (Grimm et al. 2003), we can estimate the total kinetic power output in other galaxies with known star formation rates by multiplying the HMXB kinetic luminosity estimate from equation (11) by the ratio of star formation rates relative to the Milky Way. The LMXB luminosity function does not scale as the star formation rate. Instead, it should scale as the total mass in stars (dominated by low-mass stars), of which the LMXBs are a given fraction, which is slowly increasing with time beyond a stellar age of about a billion years.
Using the stellar mass of the Milky Way, we can also calculate the time-integrated total energy that was released by low/hard state jets: The total stellar mass in the Milky Way is about \(10^{11} M_\odot M_{11}\). For a current star formation rate of \(\dot{M} \approx 3 M_\odot \text{yr}^{-1} M_{3}\), we can multiply the current power estimate from HMXBs by the star formation age of the Milky Way to derive an estimate of the total energy released by HMXB jets throughout the history of the Galaxy:

\[
E_{\text{HMXB, tot}} \approx 2.2 \times 10^{56} \text{ ergs } M_{11}/M_{10}^{0.55},
\]

while for LMXBs, we should multiply the current energy output by the age of the LMXB population, which is about \(10^{10} t_{10} \text{ yr}\), to obtain

\[
E_{\text{LMXB, tot}} = 2.3 \times 10^{56} \text{ ergs } t_{10} M_{37.8} M_{10}^{0.55}.
\]

The third quantity worth estimating from this distribution is the mean jet power of individual XRBs. The main uncertainty here is the variability of individual sources. Since the XRLF is a snapshot of the X-ray output from a large sample of sources, we have to make an assumption about how variability of individual sources factors into the XRLF. For lack of better knowledge and for simplicity, we consider two possible simplified scenarios:

1. The XRLF reflects the temporal X-ray luminosity distribution of each individual source. That is, each source spends a fraction of its life proportional to \(dN/dL(L_{X})\) in the luminosity bin \([L_{X}, L_{X} + dL_{X}]\). The luminosity range spanned by transients is certainly comparable to if not larger than the range spanned by \(L_{\text{min}}\) and \(\dot{m}_{\text{crit}}\), thus supporting this picture. Since the XRLF is rather steep, in this scenario an individual source therefore spends most of its life at low luminosities, as has long been known in the X-ray community to be the case for transient sources. The average kinetic luminosity of an individual source is simply the total kinetic luminosity of all XRBs divided by the number of black hole XRBs divided by the number of black hole XRBs in the luminosity interval \(10^{37} < L_{X} < 10^{39} \dot{m}_{\text{crit}} M_{10}\):

\[
\langle W \rangle_{\text{HMXB}} \approx 1.7 \times 10^{37} \text{ ergs s}^{-1} M_{37.8} M_{10}^{0.55},
\]

\[
\langle W \rangle_{\text{LMXB}} \approx 2.8 \times 10^{37} \text{ ergs s}^{-1} M_{37.8} M_{10}^{0.55}.
\]

These are very large numbers indeed, about 1%–2% of the Eddington luminosity for a 10 \(M_\odot\) black hole, if our estimate of \(M_{37.8}\) is at least of the right order of magnitude. This indicates that the kinetic energy transported by XRB jets is comparable to or larger than the radiative output: the integral over the luminosity functions in equations (5) and (6) gives average X-ray luminosities of \(\langle L_{X, \text{HMXB}} \rangle \sim 7 \times 10^{35} \text{ ergs s}^{-1}\) and \(\langle L_{X, \text{LMXB}} \rangle \sim 1.2 \times 10^{37} \text{ ergs s}^{-1}\), respectively. It also implies that the kinetic energy released in low-luminosity states is at least comparable to the energy advected into the black hole (see also Fender et al. 2003). We can now compare these numbers with the limits from Cyg X-1 and GRS 1915+105 from § 3.1: \(\langle W \rangle_{\text{CygX-1}} > 10^{36} \text{ ergs s}^{-1}\) and \(10^{36} \text{ ergs s}^{-1} \langle W \rangle_{\text{1915}} < \text{few} \times 10^{37} \text{ ergs s}^{-1}\), which imply \(0.1 < \langle W \rangle_{37.8} < \text{few}\), quite consistent with the estimate derived from AGN jets. In this scenario, all sources in either the HMXB or the LMXB class are assumed to be very similar, which, given the diversity of XRBs, is clearly a simplification. The fact that the XRLF is not altered by the variability of individual sources (H.-J. Grimm et al. 2005, in preparation) somewhat supports this simplified picture and the assumption that we can average over the luminosity function to remove the effects of variability.

2. Alternatively, we could consider a scenario in which each source varies around an interval in \(W_{\text{kin}}\) much narrower than the width spanned by \(L_{\text{min}}\) and \(\dot{m}_{\text{crit}}\). In this case, individual sources differ from each other in average kinetic power, and the distribution of \(\langle W \rangle\) is identical to the distribution of instantaneous power, \(W\). Still, the ensemble-averaged kinetic luminosity function \(\Phi(W_{\text{jet}})\) is identical to the snapshot kinetic luminosity function \(\Phi(W_{\text{kin}})\), and the number derived for the total kinetic power is identical to equation (11).

Neither of these scenarios is likely to be entirely correct; however, the range in \(W_{\text{kin}}\) spanned by the ensemble-averaged kinetic luminosity function in equation (7) is relatively narrow, and it is rather likely that individual sources traverse a range in \(W_{\text{jet}}\) that is as large as this. Thus, using the average value from equation (15) for individual sources to estimate the effects on the interstellar medium appears to us to be a reasonable choice.

Finally, we stress again that these estimates are based on an extrapolation from AGN jet power estimates, which themselves are somewhat uncertain and are thus working estimates only. Obviously, a much better and more accurate way to estimate \(W_{\text{kin}}\) for XRBs is a direct determination. We anticipate that conclusive measurements of \(W_0\) from XRB radio lobes (Heinz 2002) will become available in the near future.

3.3. Hysteresis and the Critical Accretion Rate

As hinted at in § 1, not only is the exact location of \(m_{\text{crit}}\) uncertain, but sources actually show a hysteresis in transitioning from the high/soft state to the low/hard state and back. The transition from high/soft to low/hard typically occurs at lower luminosities than the reverse transition. Before elaborating as to how much this affects our estimates, it is worth quickly examining what the effects of different values of \(m_{\text{crit}}\) on \(W\) and \(W_{\text{tot}}\) actually are.

We have evaluated equations (11) and (12) for a range of values of \(m_{\text{crit}}\) and fitted the results with a quadratic in log-log space. For the total jet power, we find that

\[
\log W_{\text{HMXB}} \approx 38.34 + 0.05 \log m_{\text{crit}} + 2 - 0.238(\log m_{\text{crit}} + 2)^2 + \log V_{37.8} M_{10}^{0.55}.
\]

\[
\log W_{\text{LMXB}} \approx 38.58 + 0.38(\log m_{\text{crit}} + 2)^2 + \log V_{37.8} M_{10}^{0.55}.
\]

Since the mean jet power is simply the total power divided by the number of binaries, it has the same dependence on \(m_{\text{crit}}\), but zero-order different normalizations, as given by equations (15) and (16).

This demonstrates that our estimates are not very strongly dependent on \(m_{\text{crit}}\) for values of \(m_{\text{crit}} \approx 0.01\). For LMXBs, the power changes by a factor of 1.7 when increasing \(m_{\text{crit}}\) from 0.01 to 0.1. Given that the expected range in which this hysteresis occurs is about \(0.01 < \dot{m}_{\text{crit}} < 0.1\) (Fender et al. 2004b), we can estimate the effect by assuming that sources spend an equal amount of time on the high/soft and the low/hard branches. Thus, a crude estimate would imply that about 50% of the sources above \(m_{\text{crit}} > 0.01\) are still in the low/hard state and produce jets. This would increase our estimates of the jet power for LMXBs by 36%, well within the uncertainties of our estimates. HMXBs are essentially unaffected by this change, because there are very few sources above \(m_{\text{crit}} = 0.01\).
3.4. Transient Jets

As mentioned in the introduction, some XRBs display transient jet emission associated with rapid changes in their X-ray luminosity. These events can reach radio fluxes that are much larger than in the case of steady, compact jets produced in the low/hard state. The classic example of this kind of source is GRS 1915+105 (Mirabel & Rodríguez 1994; Fender et al. 1999), the complex behavior of which is too diverse to be reviewed in the scope of this paper (see Fender & Belloni [2004] for a review of GRS 1915+105). Other transient sources for which this behavior has been observed include GRO J1655–40 (Hjellming & Rupen 1995), V4641 Sgr (Orosz et al. 2001), XTE J1748–288 (Fender & Kuulkers 2001), and XTE J1550–564 (Corbel et al. 2002; see Table 1 in Fender [2005] for more details). The radio emission from these events is typically optically thin and can be spatially resolved.

In several cases, superluminal proper motion has been detected (Mirabel & Rodríguez 1994; Hjellming & Rupen 1995; Fender et al. 1999, 2004a; Corbel et al. 2002), which implies relativistic velocities with Lorentz factors of \( \Gamma \approx 2–5 \). The relative abundance of measurable parameters in the optical thin, partially resolved case makes it possible to estimate the total energy contained in the emission region and the kinetic power in these transient jets. We briefly discuss these estimates and their implications for the total jet power from XRBs.

It is currently not understood what is the relationship between the transient jet events observed during state transitions and the steady compact jets observed in the low/hard state. It is important to stress that we cannot use the power estimates from the transient events to normalize the low/hard state kinetic luminosity function. Because we have limited the kinetic luminosity function derived above to the luminosity range typically spanned by the low/hard state, our kinetic luminosity function and the quantities derived from it do not account for the separate component contributed by these transient jets by construction.

There are several reasons why we cannot simply expand our treatment to include these sources. (1) By their nature, these events are transient, and unlike in the low/hard state, a source may or may not be emitting a transient jet at a given X-ray luminosity in a given state. The fraction of time a transient source is emitting a transient jet at a given X-ray luminosity is unknown. (2) The radio–X-ray relation that we used to derive the total power estimate from transient jets to the kinetic power should therefore be well described by equations (17) and (18) multiplied by \( \xi \), which describe the dependence of the kinetic power on the value of \( \dot{m}_{\text{crit}} \).

As already pointed out in \( \S \) 3.3, increasing \( \dot{m}_{\text{crit}} \) by an order of magnitude only increases the kinetic power estimates by a factor of \( \approx 1.7 \). Since the transient jet sources fall on essentially the same kinetic luminosity function with an unknown duty cycle \( \xi < 1 \), the ratio of the kinetic power carried in transient jets to that carried in compact, steady jets should be roughly \( 0.7\xi W_{37.8} \). This gives a total power estimate of order \( 4\xi \times 10^{38} \) ergs s\(^{-1} \) for transient jets.

On the other hand, we know from the observed number of outbursts that the total kinetic power from transient jets in the Galaxy is of the order of a few \( 10^{38} \) ergs s\(^{-1} \) (Heinz & Sunyaev 2002), compared to the total estimated power of \( \approx 5 \times 10^{38} \) ergs s\(^{-1} \). Thus, based on the estimates of \( W_0 \) we provided above and the kinetic power normalization of transient jets by Fender et al. (2004b), the integrated kinetic powers of transient jets and of compact, steady jets are of the same order of magnitude, and the duty cycle of transient jets should not be much smaller than \( \approx 10\% \).

3.5. Neutron Stars

As mentioned in \( \S \) 1, neutron stars are even less radio-loud than black hole XRBs at typical X-ray luminosities. At the present time it is not entirely clear whether the FP relation of equation (1) is applicable to neutron star systems as well: it is possible that a radio–X-ray relation exists for neutron stars, but has a different slope (Migliari et al. 2003); it is also possible that no such relation exists at all. In either case, an extension of our method is not straightforward. For simplicity, however, we assume that the same correlation shown in equation (1) holds for neutron stars as well, but with a different normalization.

Given the difference in radio-loudness of a factor of \( \approx 30 \) at a fixed X-ray luminosity and taking into account the mass difference between neutron stars and black holes of about \( M_{\text{BH}}/M_{\text{NS}} \sim 10/1.4 \), this changes the normalization of equation (1):

\[
L_r = \frac{1}{30} \left( \frac{10}{1.4} \right)^{0.78} L_\odot^{0.6} M^{0.78}.
\]

Consequently, the normalization of equations (8) and (9) changes as well:

\[
\frac{dN_{\text{NS}}}{dW_{\text{jett}}} = \left[ 30 \left( \frac{1.4}{10} \right)^{0.78/[1.42-(\alpha_*/3)]} \right]^{-\beta} \frac{dN_{\text{BH}}}{dW_{\text{jett}}}.
\]

The numerical evaluation for \( \beta = 1.6 \) in the case of HMXBs gives only a slight change of 1.1, while \( \beta = 1.4 \) in the case of LMXBs gives 1.4. Note, however, that both \( \xi \) and the mass are different for neutron stars. Taking these into account, the absolute normalization the kinetic luminosity function is increased.
by factors of 2.4 and 3.0 for neutron star HMXBs and LMXBs, respectively, compared to black hole HMXBs and LMXBs.

Fender (2005) suggests that high-field neutron star systems do not produce jets, as they show no radio emission. Since a large fraction of the neutron star HMXBs are, in fact, X-ray pulsars (Liu et al. 2000) with associated high fields, the normalization of the kinetic luminosity function for HMXB neutron stars is likely smaller by at least a factor of 2 compared to the above estimate. Furthermore, all HMXBs are believed to have rather strong fields ($B \gtrsim 10^{12}$ G), which Fender (2005) conjectured would be unable to produce jets at all. We therefore conservatively assume that the HMXB values below are upper limits.

Taking into account the lower X-ray luminosity that corresponds to $\dot{m}_{\text{crit}} = 0.01$ in neutron stars, the estimates for the mean kinetic power from neutron star jets are $(\langle W \rangle)_{\text{HMXB}} < 2.6 \times 10^{37}$ erg s$^{-1}$ $\mathcal{W}_{\text{37.8}}$ and $(\langle W \rangle)_{\text{LMXB}} \approx 2.5 \times 10^{37}$ erg s$^{-1}$ $\mathcal{W}_{\text{37.8}}$. We can then estimate the total kinetic power from neutron stars in the Galaxy to be $W_{\text{HMXB}} < 3.4 \times 10^{38}$ erg s$^{-1}$ $\mathcal{W}_{\text{37.8}}$ for HMXBs and $W_{\text{LMXB}} \approx 3.3 \times 10^{38}$ erg s$^{-1}$ $\mathcal{W}_{\text{37.8}}$ for LMXBs. This brings the total kinetic power output from XRBs (black holes and neutron stars) to $W_{\text{XRB}} \approx 9 \times 10^{38}$ erg s$^{-1}$. Finally, the total energy released by neutron star LMXB jets over the lifetime of the Galaxy is $E_{\text{LMXB}} \approx 2.2 \times 10^{56}$ ergs $\mathcal{W}_{\text{37.8}}$ $\tau_{10}$.

4. A COROLLARY: THE RADIO LUMINOSITY FUNCTION AND RADIO log $N$–log $S$ OF XRBs

Given the X-ray luminosity function for Galactic XRBs in equations (5) and (6) and the FP relation from equation (1), we can easily write down the predicted Galactic radio luminosity function for this population of binaries:

$$\frac{dN}{dlr} = \frac{dN}{d\mathcal{L}_r} \frac{d\mathcal{L}_r}{dlr},$$

(22)

where, following the nomenclature above, $l_r = L_r/L_{\text{Edd}}$ is the radio luminosity in units of the Eddington luminosity of a $1 M_\odot$ object. The top axis in Figure 1 shows the predicted cumulative radio luminosity function.

For galaxies with stellar populations of an age similar to the Milky way, the LMXB distribution should just be proportional to the mass $M$, while the HMXB distribution should be proportional to the star formation rate $\dot{M}$:

$$\frac{dN_{\text{HMXB}}}{dlr} = 10^{-0.8} \mathcal{L}_r^{-2} \mathcal{M}_{10}^{0.78} \mathcal{z}_{10},$$

(23)

$$\frac{dN_{\text{LMXB}}}{dlr} = 10^{-5.2} \mathcal{L}_r^{-5/3} \mathcal{M}_{10}^{0.52} \mathcal{z}_{10},$$

(24)

for $10^{-9} < \mathcal{L}_r < 3.2 \times 10^{-7} \mathcal{m}_{0.6}$. Again, while the total emitted radio power in the HMXB distribution seems to diverge logarithmically if the lower limit $l_{\text{min}}$ goes to zero, the luminosity function is, of course, limited by the number of sources, which is not infinite. Furthermore, the radio spectrum eventually becomes optically thin at low luminosities, and the luminosity function becomes flatter than the expression in equation (22) and converges. Note that in XRBs this transition happens at very low luminosities: For typical low/hard state sources, the break from optically thick to thin occurs in the infrared, and the break frequency $\nu_b$ roughly follows $\nu_b \propto \mathcal{L}_r^{0.1/7}$ (Heinz & Sunyaev 2003). For the break to move below radio frequencies, we would have to consider radio fluxes 8 orders of magnitude below what is typically observed.

Finally, we can estimate the flux distribution from the radio luminosity function ($\log N$–$\log S$). The flat-spectrum XRB radio flux distribution for a galaxy at distance $D$ is simply $d \log N/d \log S = 4 \pi D^2 d \log N/d \log l_r$, since all sources are essentially at the same distance. Unfortunately, it is clear from the range in luminosities implied by Figure 1 that sources in galaxies farther than about 1 Mpc will not be observable any time soon unless the population is large enough to contain significantly beamed sources (note that how relativistic the jets in XRBs actually are is still not clear; see, for example, the discussion in Gallo et al. [2003], Heinz & Merloni [2004], Kaiser et al. [2004], and Narayan & McClintock [2005]).

To derive the predicted radio flux distribution in the Milky Way, we have to convolve the luminosity function with the space distribution of binaries inside the Milky Way. Following Grimm et al. (2002) and taking $r$ and $z$ to be the radial and vertical distance to the Galactic center, the disk populations are described by the function

$$n_{\text{disk}}(r,z) = \exp \left[ -\frac{(r_m/r) - (r/r_d) - (|z|/z_d)8 \pi r_m r_d z_d}{2 K_2 \sqrt{(r_m/r_d)}} \right]$$

(25)

with $r_m \approx 4$ kpc, $r_d \approx 3.5$ kpc, and $r_d \approx 410$ pc for LMXBs, and $r_m \approx 6.5$ kpc, $r_d \approx 3.5$ kpc, and $r_d \approx 150$ pc for HMXBs, and $K_2$ is the modified Bessel function of the second kind. The LMXB distribution also requires a spherical halo component, which we assume to follow the relation

$$n_{\text{halo}}(R_h) = \frac{b^{8.5} e^{-b(R/R_h)}}{16 \pi R_h^2 \Gamma(8.5)} \left( \frac{R_h}{R_c} \right)^{7/8}$$

(26)

with $b \approx 7.7$ and $R_c \approx 2.8$ kpc. Finally, about 30% of the disk sources reside in the Galactic center population, at about 8 kpc distance, for which we use the distribution

$$n_{\text{bulge}}(R) = \frac{(R/R_0)^{-1.8} e^{-b(R/R_c)}}{2 \pi \Gamma(0.4) R_0^{1.8} R_{1/2}^{1/2}}$$

(27)

with $R_0 = 1.0$ kpc and $R_{1/2} = 1.9$ kpc.

The fraction of LMXBs in the halo is approximately 25% (including globular cluster sources). We take the functional form of the luminosity function to be the same for the halo, bulge, and disk components. We then integrate over the luminosity function plotted in Figure 1 and arrive at the flux distribution shown in Figure 2 for different values of the upper and lower cutoffs $l_{\text{min}}$.
and $h_{\text{crit}}$. The thick lines indicate the fiducial luminosity interval of $10^{-4} < L_{\text{x}} < 10^{-1}$. Note that these are time-averaged curves. Temporal variability necessarily introduces large uncertainty at the high-flux end, where few sources contribute at a given time.

Since we know at least one HMXB source that emits regularly at 10 mJy levels (Cyg X-1) and a spectrum of other transient sources that regularly pass above the 10 mJy line, the HMXB curve derived for the fiducial parameters can safely be regarded as a lower limit.

Clearly, the question of how far the X-ray luminosity function extends to lower luminosities and where the radio–X-ray relation breaks down has large implications for the number count of sources at lower fluxes. In other words, extending the sensitivity of XRB monitoring campaigns to lower fluxes will reveal rather quickly below which radio luminosity the predicted radio luminosity function breaks down.

Finally, it should be noted that this is essentially the probability distribution of finding a given binary at a given distance from Earth, convolved with the predicted radio luminosity function. Since the actual number of XRBs is small, the error bars on this curve, especially for large fluxes, are probably large. However, a realistic assessment of the uncertainties in this distribution is beyond the scope of this paper.

5. CONCLUSIONS

Starting from the observed radio–X-ray–mass relation for accreting black holes and the observed X-ray luminosity function for XRBs, we derived the predicted kinetic luminosity function of compact jets from Galactic black holes in the low/hard state. The integration over the kinetic luminosity function of compact jets yields estimates of the average kinetic power output of $\langle W_{\text{jet}} \rangle \sim 2 \times 10^{37}$ erg s$^{-1}$ (dominated by LMXBs) and total integrated kinetic energy input over the history of the Galaxy of $E_{\text{tot}} \sim 4.5 \times 10^{56}$ ergs. We argue that transient jets should carry a comparable amount of power. We also derived the predicted radio luminosity function and the radio flux distribution for XRB jets. These estimates can be used in future modeling of XRB jet parameters and provide a baseline for estimating the impact of XRB jets in the interstellar medium.

Note added in manuscript.—After submission of this manuscript we became aware of a related paper (Fender et al. 2005), recently accepted for publication in MNRAS, that reaches similar conclusions.

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