The stringent upper limit on jet power in the persistent soft-state source 4U 1957+11

Thomas J. Maccarone,[1]★ Arlo Osler,[1,2] James C. A. Miller-Jones [ID],[3] P. Atri [ID],[3]
David M. Russell [ID],[4] David L. Meier,[5] Ian M. McHardy[6] and Penelope A. Longa-Peña[7]

[1]*Department of Physics & Astronomy, Texas Tech University, Box 41051, Lubbock TX 79409, USA*
[2]*Department of Physics, Pima Community College, Tucson AZ 85709, USA*
[3]*International Centre for Radio Astronomy Research, Curtin University, GPO Box U1987, Perth, WA 6845, Australia*
[4]*Center for Astro, Particle and Planetary Physics, New York University Abu Dhabi, PO Box 129188, Abu Dhabi, UAE*
[5]*Jet Propulsion Laboratory, Pasadena, CA 91109, USA*
[6]*University of Southampton, Southampton SO17 1BJ, UK*
[7]*Universidad de Antofagasta, Antofagasta, Chile*

ABSTRACT

We present extremely deep upper limits on the radio emission from 4U 1957+11, an X-ray binary that is generally believed to be a persistently accreting black hole that is almost always in the soft state. We discuss a more comprehensive search for Type I bursts than in past work, revealing a stringent upper limit on the burst rate, bolstering the case for a black hole accretor. The lack of detection of this source at the 1.07 μJy/beam noise level indicates jet suppression that is stronger than expected even in the most extreme thin disc models for radio jet production – the radio power here is 1500–3700 times lower than the extrapolation of the hard state radio/X-ray correlation, with the uncertainties depending primarily on the poorly constrained source distance. We also discuss the location and velocity of the source and show that it must have either formed in the halo or with a strong asymmetric natal kick.

Key words: proper motions – stars: jets – X-rays: binaries – X-rays: individual: 4U 1957+11.

1 INTRODUCTION

Relativistic jets provide a strong impact on a variety of important processes in the Universe. The jets from supermassive black holes provide one of the primary sources of feedback into the interstellar medium (Silk & Rees 1998), as well as one of the main mechanisms for accelerating the highest energy particles in the Universe (Hillas 1984). Because the jets may be powered by rotating black holes (Blandford & Znajek 1977), understanding the mechanism for producing strong jets and the factors with which jet power correlates may yield new means for probing the spin distribution of black holes. This may be especially useful for purposes like associating the environments of supermassive black holes with their spin histories, which requires large samples that probably preclude the source-by-source approaches such as reflection modelling (García et al. 2014) that have the best potential for giving precise spin estimates of individual systems.

Direct studies of supermassive black holes suffer from a variety of challenges not applicable to stellar mass black holes. Supermassive black holes show only weak, stochastic variability on human time-scales, while stellar mass black holes often show factors of 10^6 or more variability on time-scales of months. Furthermore, the mass estimates for stellar mass black holes are generally more precise and have systematics that are better understood, with clearer paths to improvement. Thus, developing an understanding of how processes work in X-ray binaries and extrapolating those results to supermassive black holes is a fruitful approach (see e.g. Merloni, Heinz & di Matteo 2003).

One of the first clear results in understanding jet formation that came from X-ray binaries is that in spectral states dominated by soft X-rays, with strong thermal emission, the jet power is significantly weaker than in systems where the emission is dominated by hard X-rays (Tananbaum et al. 1972). Unfortunately, the excitement surrounding the discovery of the correlated X-ray and radio transitions from Cygnus X-1 was, at the time, primarily that it provided evidence for a radio counterpart to the X-ray source, yielding good enough angular resolution to verify the correct optical counterpart. It was thus about two decades before the significance of this discovery was fully appreciated, and it was found that the strong correlation between hard X-ray emission and radio emission was ubiquitous (Harmon et al. 1995; Hannikainen et al. 1998; Fender et al. 1999).

Theoretical work has since established a framework in which these correlations can be understood. Jets are most likely to be powered by the poloidal components of the magnetic fields of their host accretion discs. In the soft spectral states, the accretion discs are well modelled as geometrically thin, optically thick discs, with the spectra being produced as the sum of a series of diluted blackbodies (Novikov & Thorne 1973; Shakura & Sunyaev 1973; Davis & Hubeny 2006). This approach yields a remarkably good spectral model for the existing data. When the hard X-rays dominate, the emission is most likely to

★ E-mail: thomas.maccarone@ttu.edu

come from Compton upscattering in a geometrically thick, optically thin medium (Thorne & Price 1975; Sunyaev & Truemper 1979). Since the geometric scale height of the accretion flow near the black hole is then dramatically larger, the poloidal component of the magnetic field should be larger.

Most black hole X-ray binaries spend most of their lives in the 'hard' and quiescent spectral states. In typical soft X-ray transients, sources remain in faint hard states for long periods of time, undergo a disc instability that triggers a rapid rise in luminosity, and follow through a hysteresis loop in which they make transitions from hard to soft at higher luminosities than they make transitions from soft to hard (Miyamoto et al. 1995; Maccarone & Coppi 2003). Very strong radio flaring is generally seen in the hard-to-soft transitions, but not in the soft-to-hard transitions, and this has been interpreted as arising from the fast ejecta launched at the state transitions running into denser, slower moving ejecta from the previous long-lasting hard state when the hard-to-soft transition occurs, while, at the soft-to-hard transition, there are no nearby ejecta present (e.g. Vadawale et al. 2003). In Cygnus X-3, the radio emission is enhanced in all spectral states relative to other sources, and the strongest flaring is seen at the return from the soft state to the more common hard states (Koljonen et al. 2013). This is explained best by a scenario in which the working surface for the jet in Cygnus X-3 is not other jet matter, but is the stellar wind, so that when the jet turns off for an extended period of time in the soft state, the wind has an opportunity to fill in the cavity that had been evacuated (Koljonen et al. 2018).

Soft-state detections from the stellar mass black holes that mostly are in hard states (e.g. Rushton et al. 2012) may represent either *bona fide* soft-state powering of the jet or leftover transient emission. Soft-state detections from Cyg X-3 are likely to be powered, at least in part, by the very strong free–free emission from the Wolf Rayet donor star's wind, or a collision between the WR wind and the disc wind from the accretor (Waltman et al. 1996; Koljonen et al. 2018) rather than from the jet at all. The ideal location to probe unambiguously the soft-state jet power is a low-mass X-ray binary that is persistently or nearly persistently in a soft state.

One X-ray binary, 4U 1957+11, is a persistent source, nearly always in the high/soft state and is generally believed to have a black hole accretor (e.g. Nowak et al. 2012; Gomez, Mason & Robinson 2015, although see also Bayless et al. 2011). While the persistent brightness makes it difficult to make precise mass and distance estimates, the persistent softness still makes it the ideal source in which to look for the most extreme reduction in radio power relative to standard correlations. In Russell et al. (2011), we have already established this source to have its jet power suppressed by a factor of 330–810 relative to hard state X-ray binaries at the same X-ray luminosity with the uncertainties mostly due to distance uncertainties. Here, we present the results of observations with a flux density 3.4 times lower, in conjunction with a slightly higher X-ray flux, providing evidence for jet suppression by a factor of at least 1500. We also discuss its astrometric properties and the strong evidence that it either formed in the Galactic halo or formed with a very strong natal kick, an issue already raised in Nowak et al. (2012), which we can address in more detail here.

2 DATA

2.1 Radio data

The Karl G. Jansky Very Large Array (VLA) observed 4U 1957+11 for a total of 21 h in 14 observing sessions between 2014 February 20 and March 23, with 17 h on source, and 4 h for calibration and slewing. The data were collected between 8 and 10 GHz under project code 14A-256. Two of the observations (on February 22 and 23) were very badly affected by radio frequency interference in the non-linear regime and were excluded. The phase calibrator for the observations was J1950+0807, and the flux calibrator was 3C 48. The data were reduced using standard procedures in CASA (McMullin et al. 2007), and we obtain a noise level of 1.07 μJy/beam for the full data set.

2.2 X-ray data

Because of the large number of dynamically scheduled radio observations, along with the high brightness of the source in X-rays, we chose to use all-sky monitor data in the X-ray band rather than to obtain new X-ray data. The Monitor of All-sky X-ray Image (MAXI – Matsuoka et al. 2009) data for the source show a weighted mean count rate of 0.103 cts s^{-1} cm^{-2} in the date range from MJD 56712.5 to 56739.5, over which the data were taken. This corresponds to a flux of 1.1×10^{-9} erg s^{-1} cm^{-2} (2–20 keV) for thermal models within the range typically seen from this source (Nowak et al. 2012).

Additionally, we look at the X-ray data from proposal 50128 (PI: Nowak), the longest campaign on the source by the Rossi X-ray Timing Explorer (Swank 2006). This campaign had about 300 kiloseconds of data on source. We look at these data to determine whether any Type I X-ray bursts took place. The least frequent burster among the 'banana state' neutron star systems is Ser X-1 (Galloway et al. 2008), which bursts about once per 8 h. It had already been found in 26 kiloseconds of data that 4U 1957+11 shows no Type I bursts (Wijnands, Miller & van der Klis 2002), which already provided suggestive evidence that it is not a soft-state accreting neutron star. With this additional data set of 300 kiloseconds, about 10 bursts would have been expected if the source bursted as frequently as Ser X-1, and the lack of bursts thus provides very strong, albeit non-dynamical, evidence against a neutron star accretor.

3 THE POSITIONAL AND BINARY SYSTEM PARAMETERS FOR 4U 1957+11

3.1 The orbital period and nature of the donor star

Because 4U 1957+11 has never gone into quiescence, its optical flux has consistently been dominated by its accretion disc, rather than by its donor star. An orbital period of 9.33 h has been measured from photometric modulations (Thorstensen 1987), likely due to illumination of the donor star by the accretion disc (Thorstensen 1987; Bayless et al. 2011). Emission lines give a tentative mass ratio of ≈0.3 (Longa-Peña 2015) but neither reliable direct radial velocity curves of the donor star's absorption lines nor inclination angle estimates from the orbital data have been produced.

The donor star may be slightly evolved. A halo star is possible but would have to be towards the metal-rich end of the halo star distribution and to be slightly evolved; 10-Gyr old stars filling a Roche lobe at a period of 9.3 h with [Fe/H] ≈ −1 can still have cool enough envelopes to allow convection (Pietrinferni et al. 2006). For donors that are significantly more metal poor, stars that fill this Roche lobe will have radiative envelopes even after 10 Gyr, suppressing magnetic braking, and hence would not have substantial mass transfer rates.

3.2 Astrometry and possible halo nature

The object is detected in *Gaia* DR2 (Gaia Collaboration 2018) with a parallax measurement of 0.025 ± 0.239 mas and a proper motion

of -0.19 ± 0.36 mas yr^{-1} in RA and of -1.94 ± 0.29 mas yr^{-1} in declination. After correcting for the global zero-point offset of -0.029 mas in *Gaia*'s parallax measurement (Luri et al. 2018; Chan & Bovy 2020), the parallax measurement can be used to constrain the distance to the source with the use of an appropriate prior. For 'normal' stars, Bailer-Jones et al. (2018) provide such a prior. Because X-ray binaries typically have a larger scaling height than disc stars, we use a Milky Way-like prior (Atri et al. 2019) with scale height parameters derived in Grimm, Gilfanov & Sunyaev (2002) for X-ray binaries. We determine the posterior distance distribution to the source with a median of 7 kpc and 5th and 95th percentile of 3 and 15 kpc, respectively (see Fig. 1, left-hand panel). We note that some additional considerations based on the X-ray properties, discussed in the next subsection, disfavour the lower end of this range.

The centre of mass radial velocity, γ of the binary, is -180^{+30}_{-38} km s^{-1} (Longa-Peña 2015). This comes from Bowen fluorescence measurements. Given that this source is located at a Galactic longitude of $+51$ deg, it is expected that its radial velocity would be positive, not negative. As a result, it must have had a substantial natal kick, or it must be a halo system. We used the proper motion, the systemic radial velocity, and the distance constraints derived above to constrain the current three-dimensional space velocity of the system. The age of the system is unknown but most X-ray binaries are assumed to be born in the Galactic plane. We use *galpy* (Bovy 2015) and Monte Carlo simulations to integrate and sample 5000 Galactocentric orbits of the system and derive the probability distribution for the peculiar velocity of the system when it crosses the Galactic plane, called the potential kick velocity (PKV, Atri et al. 2019). As can be seen in Fig. 1 (right-hand panel), the PKV distribution of the system has a median of 346 km s^{-1}, with a 5th and 95th percentile of 203 and 594 km s^{-1}, respectively. Due to the large uncertainty on the *Gaia* parallax, we also test a loosely constrained uniform distance prior of 5–25 kpc and find that the PKV distribution is not affected considerably, with a median of 360 km s^{-1}, and 5th and 95th percentiles of 215 and 602 km s^{-1}, respectively. Thus, regardless of the distance of the source, the PKV of the system is always in excess of 100 km s^{-1}.

The PKV distribution of the source is too large to be accommodated in a straightforward manner with just the Blaauw (1961) mechanism of mass loss from a moving component of a binary. The maximum kick in such a scenario is given in Nelemans, Tauris & van den Heuvel (1999) as:

$$v_{sys} = 213 \left(\frac{\Delta M}{M_\odot} \right) \left(\frac{m}{M_\odot} \right) \left(\frac{P_{re-circ}}{day} \right)^{-1/3}$$

$$\times \left(\frac{M_{BH} + m}{M_\odot} \right)^{-5/3} \text{km/s}, \quad (1)$$

where ΔM is the mass lost during the supernova (limited to half the total system mass if the system remains bound after the supernova), m is the donor mass, M_{BH} is the black hole mass, and $P_{re-circ}$ is the period of the binary after re-circularization. Allowing for substantial mass transfer in the system to have already taken place, 100 km s^{-1} could be achieved, but 200 km s^{-1} cannot be achieved without very unreasonable assumptions. The possible range of kicks could easily be produced if there is an asymmetric natal kick (Brandt & Podsiadlowski 1995). This would make the system the fastest moving black hole X-ray binary known in our Galaxy.

The potential halo nature of the object is intriguing. For this object, the strengths of the Bowen fluorescence lines are typically a factor of 2 weaker than the He II emission lines at 4686 Å (Longa-Peña 2015). In most other systems, the Bowen lines are stronger than the

He II lines. Without careful photoionization modelling, this does not definitively indicate that the abundance ratio of helium to carbon and nitrogen is anomalously high for this system, but it does indicate that this is potentially the case and hence worth such an investigation. This tentative evidence for a halo origin plays against the low mass of the black hole, given that low metallicity environments lead to weaker winds and more massive remnants, while the highest kick black holes are expected to be the least massive ones (Belczynski & Bulik 2002).

3.3 X-ray properties and the question of black hole versus neutron star accretor

There is no direct evidence for a black hole in this system. There is some evidence that if the system contains a black hole, the black hole is toward the low-mass end of the mass spectrum (Nowak & Wilms 1999), possibly in the 'mass gap' between 2 and 5 $M_\odot$ (Özel et al. 2010; Farr et al. 2011). Bayless et al. (2011) make a series of arguments, none of which they claim to be conclusive, that suggest that the system contains a neutron star. The two most important of these arguments are (1) the lack of superhumps seen in the system, and (2) the amplitude of the optical periodicity. It is not clear that the lack of superhumps is strongly constraining; the ratio of viscous heating to reprocessing in X-ray binaries in the optical band is much lower than in cataclysmic variables, and the strength of superhump emission is significantly weaker (Haswell et al. 2001; Russell et al. 2010). The amplitude of the orbital periodicity is also used by Bayless et al. (2011) to argue for a relatively small mass ratio, but here, the conclusions depend strongly on the inclination angle of the system and assumptions about the size of the accretion disc relative to its circularization radius and its temperature. Longa-Peña (2015) also find evidence for a mass ratio of 0.25–0.3 from the ratios of the amplitudes of the radial velocity curves for the accretion disc and the donor star as inferred from emission lines of both. All these results are consistent with a black hole of relatively low mass ($\sim4 M_\odot$), as long as one understands that the optical superhumps may be quite weak in a system where the optical emission is dominated by reprocessing. Furthermore, using a similar approach to that of Bayless et al. (2011) with a larger data set, Gomez et al. (2015) conclude that a low-mass black hole is the most likely accretor.

The X-rays from the source consistently exhibit low-amplitude variability ($\lesssim 2$ per cent rms amplitude) and show a very soft spectrum, with rare instances at the faint end of the luminosity range for the source where it shows some tentative increase in the characteristic radius of the accretion disc and strength of the power-law component, possibly indicating an intermediate state (Nowak et al. 2012). Black hole X-ray binaries show this behaviour in their 'soft states', which typically occur above 2 per cent of the Eddington luminosity (Maccarone 2003; Vahdat Motlagh, Kalemci & Maccarone 2019). Neutron stars tend to show this low-amplitude variability behaviour in 'banana states', which also occur in the same Eddington fraction range (Maccarone 2003). This likely gives a distance of ≈15 kpc for a black hole X-ray binary, and for a neutron star X-ray binary, it gives a value of ≈7 kpc. The most likely range of distances thus excludes most of the range with the slowest velocities, bolstering the case made above for a halo orbit, regardless of whether that orbit results from birth in the halo or a strong natal kick.

Beyond this, we can also consider the likely range of accretion rates for the source based on binary stellar evolution. Re-scaling equation (9) of King, Kolb & Burderi (1996) (and leaving out the negligible gravitational radiation component), we can see that, for a
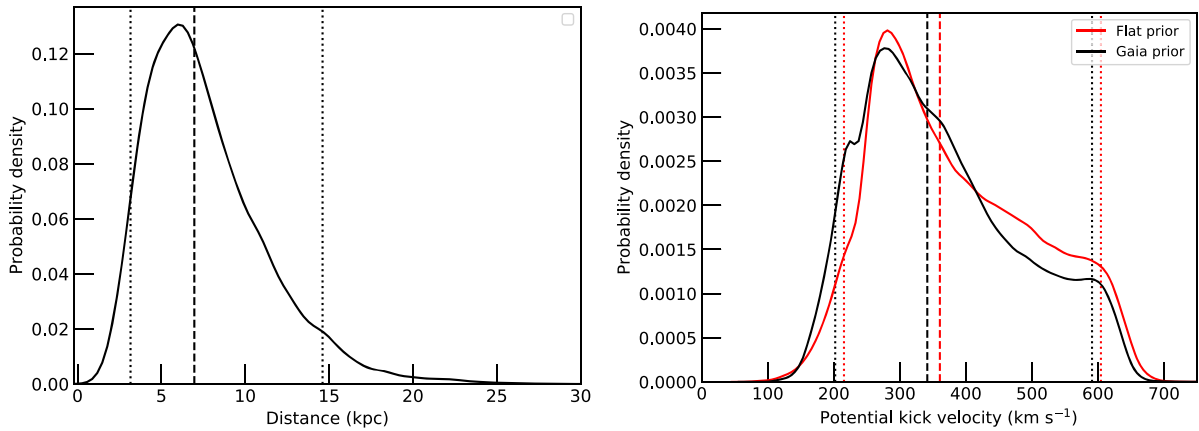
Figure 1. Left-hand panel: The posterior distance distribution of 4U 1957+11, using the *Gaia* parallax constraints, along with the assumptions described in the main text about the spatial distribution of X-ray binaries. Right-hand panel: Potential kick velocity distribution of 4U 1957+11, using both the *Gaia* distance prior (black solid line) and a uniform distance distribution prior (red solid line). The kick velocity distribution in both cases does not go below 100 km s^{-1}, suggesting that the system received a strong natal kick at birth, or formation in the halo. Dashed lines in both the panels represent the median and the dotted lines represent the 5th and 95th percentiles of the distribution.

9.33-h orbital period, the mass transfer rate can be expected to be:

$$\dot{m}_2 = 4 \times 10^{17} \left(\frac{m_1}{3M_\odot} \right)^{-2/3} \left(\frac{m_2}{0.93M_\odot} \right)^{7/3} \text{ g s}^{-1}, \quad (2)$$

with the mass transfer due to magnetic braking. Taking this accretion rate, we find that if the donor is a main-sequence star, the X-ray luminosity will be 6×10^{37} erg s^{-1} if the source is an accreting neutron star, at about 30 per cent of the Eddington luminosity for a standard accreting neutron star, making it likely to show the strong variability characteristic of the Z-sources. For an accreting black hole, it will be at about 2–4×10^{37} erg s^{-1}, perhaps a bit brighter if the black hole is rapidly rotating and hence more radiatively efficient, as has been suggested based on its hot accretion disc (Nowak et al. 2012). If the donor star is a mildly evolved halo star, the $m_2^{7/3}$ term may cancel out the increased efficiency due to the deeper potential well for the rotating black hole. Binary evolution thus provides another argument in favour of a black hole nature (in addition to the X-ray spectral considerations already presented in Nowak et al. 2012 and the lack of Type I bursts discussed above). The sum total of these arguments is that there is reasonably good evidence for a black hole of lower mass than is typically seen in low mass X-ray binaries, but that there is also strong, albeit not dynamical, evidence against a neutron star.

4 THE JET POWER SUPPRESSION RATE

The 3-σ upper limit on the radio flux density from the source is 3.2 μJy. In Russell et al. (2011), we established a flux density limit of 11.4 μJy, which yields a jet radio power suppression of a factor of 330 (at 20 kpc) to 810 (at 7 kpc) relative to the standard black hole X-ray binary correlation from Gallo, Fender & Pooley (2003). Retaining the same distance range in Russell et al. (2011), we find that the suppression, given the 3-σ flux upper limit, is a factor of 1500–3700 relative to the radio/X-ray correlation in the hard state, with some of the additional size of the effect coming from the X-ray flux being 1.25 times as high as in those observations. If we restrict ourselves to the upper end of the distance range, based on the arguments above related to the likely accretion rate of the source, then we end up toward the lower end of the range.

The other sources that have shown comparably extreme jet suppression are H1743-322 (Coriat et al. 2011), with a factor of about 700 and MAXI J1535-571 (Russell et al. 2019), with a factor of about 3000. We note that the presence of a 'radio-quiet' track in the hard state (Coriat et al. 2011) does not strongly affect this result – these systems have steeper correlations than those in Gallo et al. (2003) but join to the standard correlation for the brightest and faintest hard states.

5 DISCUSSION

Meier (2001) has worked out expected jet powers for different accretion disc models. While numerical calculations have advanced dramatically since the work of Meier (2001), it is still the case that the most sophisticated treatments of general relativistic MHD work best for systems at low-accretion rate, because increasing the accretion rate increases the computational time (e.g. Liska et al. 2019). As a result, we still use the semi-analytic work of Meier (2001) as our basic framework for interpreting the results.

5.1 Radiatively inefficient jets: unlikely in light of Cyg X-3

An alternative to the scenario in which the jets have their power suppressed is one in which power is injected into the jets, but the power is not effectively dissipated, so that the ratio of radio power to kinetic power is substantially smaller than in hard states. In most systems, this could occur for a few reasons – Poynting flux domination (Lovelace et al. 2002) or poor dissipation of the power due to the lack of variability (Drappeau et al. 2017). The results on Cygnus X-3, where the return from the soft to hard state is where the strongest jet emission is seen (Koljonen et al. 2018), strongly argue that the jets genuinely turn down in power during the soft state. In principle, Poynting flux could pass through the stellar wind without being dissipated, and numerical calculations specific to this problem, but outside the scope of this paper, should be done to test this possibility, but one of the original motivations for considering Poynting flux jets over matter-dominated jets was to *increase* the radiative efficiency (Giannios & Spruit 2005). The Cyg X-3 results are more clearly problematic for the weak dissipation model of

Drappeau et al. ([2017](#)). Shocks will necessarily develop against the stellar wind, whose velocity is roughly perpendicular to the jets in the inner jet region, and this will be true regardless of the level of velocity variability in the ejected material.

5.2 A Schwarzschild black hole in 4U 1957+11: unlikely to be the case or to cause the effect

At least according to theoretical work, jet power can be strongly suppressed in all spectral states if a black hole has a low rotation rate. Observational work on this topic indicates mixed results; relatively little evidence exists for spin affecting the production of jets in hard states (e.g. Fender, Gallo & Russell [2010](#); Russell, Gallo & Fender [2013](#); McClintock, Narayan & Steiner [2014](#); Middleton, Miller-Jones & Fender [2014](#)) and may result from the correlation of both inferred spin and peak L_X with period (Wu et al. [2010](#)). The spin–period correlation may have a physical origin if, e.g. black holes grow dramatically after birth (Fragos & McClintock [2015](#)), while the period–X-ray peak correlation has a very clear physical explanation in the larger accretion discs at longer period (Wu et al. [2010](#)).

Several investigations of the spin of this black hole have been made, via disc continuum fitting (Nowak et al. [2012](#); Maitra et al. [2014](#)). All favour the idea that the black hole is rapidly rotating and furthermore find that the distance must be at least 10 kpc in the context of this model (and that would require a low black hole mass of $3 M_\odot$ – Nowak et al. [2012](#)).

5.3 Fundamentally low jet power?

The alternative then is that the jet power is fundamentally lower in the soft state than in the hard state. One possibility is that the analytic work of Meier ([2001](#)) is not a good approximation to reality, and the process of accelerating the jets, and that the magnetic forces are much less effective at extracting power from soft-state black holes relative to hard state black holes. If the scalings of jet power to disc properties are correct, then this would indicate that the accretion discs in soft states are substantially thinner than the approximations used by Meier ([2001](#)), or, more likely, that the ad hoc assumptions made about the ratios of their large-scale magnetic fields to their dynamo fields scale. Additionally, the low mass of the black hole may be responsible for a factor of $\sim$1.5 reduction in the ratio of radio power to jet power (Merloni et al. [2003](#)). We regard this combination of effects as the most likely possibility at the present time, but we also encourage more theoretical work to determine if the jet power may be genuinely suppressed by a larger factor in the soft states than previously estimated.

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