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THE FIRST POLARIMETRIC SIGNATURES OF INFRARED JETS IN X-RAY BINARIES

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ABSTRACT

We present near-infrared linear spectropolarimetry of a sample of persistent X-ray binaries, Sco X-1, Cyg X-2, and GRS 1915+105. The slopes of the spectra are shallower than what is expected from a standard steady state accretion disk, and can be explained if the near-infrared flux contains a contribution from an optically thin jet. For the neutron star systems, Sco X-1 and Cyg X-2, the polarization levels at 2.4 μm are 1.3% ± 0.10% and 5.4% ± 0.7%, respectively, which is greater than the polarization level at 1.65 μm. This cannot be explained by interstellar polarization or electron scattering in the anisotropic environment of the accretion flow. We propose that the most likely explanation is that this is the polarimetric signature of synchrotron emission arising from close to the base of the jets in these systems. In the black hole system GRS 1915+105 the observed polarization, although high (5.0% ± 1.2% at 2.4 μm), may be consistent with interstellar polarization. For Sco X-1 the position angle of the radio jet on the sky is approximately perpendicular to the near-infrared position angle (electric vector), suggesting that the magnetic field is aligned with the jet. These observations may be a first step toward probing the ordering, alignment, and variability of the outflow magnetic field in a region closer to the central accreting object than is observed in the radio band.

Subject headings: accretion, accretion disks — binaries: close — stars: individual (Cygnus X-2, GRS 1915+105, Scorpius X-1)

1. INTRODUCTION

In the past decade or so overwhelming evidence has pointed to a clear coupling between accretion and the formation of relativistic jets in galactic X-ray binary systems (see Fender 2006). Accretion states associated with hard X-ray spectra appear to be associated with the production of a relatively steady, continuously replenished, and partially self-absorbed outflow (Fender 2001), while major outbursts are associated with more discrete ejection events that may be resolved and tracked with radio interferometers (e.g., Mirabel & Rodríguez 1994).

In the radio band the steady jets observed during the hard X-ray states have a flat (α ∼ 0, where Sν ∝ να) spectrum, probably resulting from self-absorption in a self-similar outflow (e.g., Blandford & Konigl 1979). Above some frequency this flat spectral component should break to an optically thin spectrum (α ∼ −0.6) corresponding to the point at which the entire jet becomes transparent. There is some evidence from some black hole X-ray binaries that this break occurs around the near-infrared spectral region (e.g., Corbel & Fender 2002; Nowak et al. 2005; Homan et al. 2005; Russell et al. 2006), something that can be well fit by jet models (Markoff et al. 2001, 2003). Thus the case is strong that there is a significant contribution of synchrotron emission, probably optically thin, in the near-infrared spectral regimes of X-ray binaries. However, one key test which is yet to be reported is a measurement of the linear polarization in this regime. Not only would a high level of linear polarization confirm the synchrotron interpretation, it would offer us the opportunity to study the degree of ordering and orientation of the magnetic field at the base of the jet. In this paper we present near-infrared spectropolarimetry for a sample of luminous X-ray binaries, all of which can be confidently identify as jet sources based on radio observations.

2. OBSERVATIONS AND DATA REDUCTION

We obtained HK spectropolarimetry of three X-ray binaries Sco X-1, Cyg X-2, and GRS 1915+105 with UKIRT during the nights of 2004 July 18, 19, 22, and 23. UIST was used with the HK (1.4–2.5 μm) grism and the InSb array with a 2 pixel wide slit, giving a spectral resolution of 680 km s−1 at 2.2 μm. We used the IRPOL2 polarimetry module, which comprises of a half-wave retarder, a focal plane mask, and a Wollaston prism that splits the light from each aperture mask into orthogonally polarized ordinary (o-) and extraordinary (e-) beams, which are then projected onto the array. Rotating the half-wave retarder to 0.0°, 45°, 22.5°, and 67.5° allowed us to obtained spectropolarimetry. The normalized Stokes parameters are then determined from ratios of the two intensities measured in each frame, canceling any changes in sky transmission between images.

To determine the polarization spectrum we took short exposures of the target and sky pair (obtained by nodding the target along the slit) at the four half-wave retarder positions, giving rise to eight spectra of the target and a measurement of the polarization state of the target. The target spectra were proceeded by observations of an F or A star, which were used to remove the telluric atmospheric features. Furthermore, observations of a non-polarized object and a polarized object were observed to determine the instrumental polarization level and positional angle. A journal of observations is presented in Table 1.

The ORAC-DR pipeline was used to reduce the data, extract the spectra and determine the polarization state of the targets. First the bad pixel mask was applied and then the images were dark-subtracted, flat-field, and sky-subtracted. The o- and e-beams were then optimally extracted (which also allows for any slight spectral tilt) and wavelength calibrated using the Argon arc (rms error of 1.7 Å). Lazzati et al. (2003) have noted that the values of the shape of the polarization spectrum can depend on the extraction technique. We used different methods (optimal, normal

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extracts (and tracing) and find no such dependency. POLPACK was then used to determine the intensity $I$ and the Stokes $Q$ and $U$ vectors. The flux calibration was done by using the telluric star. The target spectra were divided by the telluric star (with the stellar features interpolated), and then multiplied by the flux of the telluric star, determined from a blackbody function with the same effective temperature and flux as the telluric star.

3. SPECTRA

In Figure 1 we show the dereddened $HK$ spectra of Sco X-1, Cyg X-2, and GRS 1915+105 using color excess $E(B-V)$ values of 0.3 (Vrlíček et al. 1991), 0.4 (Orosz & Kuulkers 1999), and 6.3 (Chapuis & Corbel 2004), respectively, and the extinction law from Howarth (1983). The $H$ and $K$ slit magnitudes obtained after integrating the spectra with the filter responses are as follows: $H = 11.6, K = 11.5$ for Sco X-1, $H = 13.2, K = 13.0$ for Cyg X-2, and $H = 11.7, K = 11.4$ for GRS 1915+105. The dereddened spectra can be described as a power law from Howarth (1983). The polarization level. For GRS 1915+105 the opposite is the case. In Figure 2 we show the wavelength binned polarization spectrum for Sco X-1, Cyg X-2, and GRS 1915+105 using color excess $E(B-V)$ values of 0.3 (Vrlíček et al. 1991), 0.4 (Orosz & Kuulkers 1999), and 6.3 (Chapuis & Corbel 2004), respectively, and the extinction law from Howarth (1983). The $H$ and $K$ slit magnitudes obtained after integrating the spectra with the filter responses are as follows: $H = 11.6, K = 11.5$ for Sco X-1, $H = 13.2, K = 13.0$ for Cyg X-2, and $H = 11.7, K = 11.4$ for GRS 1915+105. The dereddened spectra can be described as a power law from Howarth (1983). The polarization level. For GRS 1915+105 the opposite is the case.

4. POLARIZATION

For each target we obtain eight spectra for each single set of observations of a target star. At each of the four wave-plate angles, we measure the flux in the two orthogonal ($o$- and $e$-) polarizations. These measurements are combined to produce the normalized Stokes $q = (Q/I)$ and $u = (U/I)$ spectra. The polarization spectrum $p$ and position angle $\theta$ is then be calculated using $p = (q^2 + u^2)^{1/2}$ and $\theta = 0.5 \tan^{-1}(u/q)$, respectively. The Stokes parameters may contain some component of instrumental polarization introduced by reflections within the telescope and detector optics. The instrumental polarization was determined from the nonpolarized standard star observed each time the science target was observed, and was typically <0.1%.

The level and quality of the polarization spectra were not sufficient enough to allow us to resolve the variations in the polarization level across the major emission lines. The only reliable information that could be extracted was the continuum. In Figure 2 we show the wavelength binned polarization spectrum for our targets. For Sco X-1 we could not determine $\theta$ on UT 20040719 and so the polarization of the source was not detected. Hence, we only averaged the individual Stokes $q$ and $u$ vectors on UT 2004 July 18 and 23 before calculating the polarization spectrum. As one can see, Sco X-1 and Cyg X-2 both show polarization spectra that increase at longer wavelengths (lower frequencies); i.e., the 2.4 $\mu$m polarization is larger than the 1.65 $\mu$m polarization level. For GRS 1915+105 the opposite is the case.
order to demonstrate that the trends observed in our science targets are genuine, we also show the polarization spectrum of a polarized standard star HD 183143 determined in exactly the same way as for the science targets. The polarization spectrum is as expected (Gehrels 1974). In Table 2 we give the polarization and position angle values. Although the polarization standard HD 183143 can be used as a validation of the data reduction method, the standard is bright while the targets are faint, close to the sky background level, and so poor sky subtraction may introduce a correlation between target brightness and polarization level. However, it should be noted that Sco X-1 and GRS 1915+105 have similar magnitudes but very different levels of polarization. To calculate the mean polarization at 1.65 and 2.4 μm, we assume that the Stokes vectors do not change over 0.10 μm, we as-
sume that the Stokes vectors do not change over 0.10 μm.

![Fig. 2.—From top to bottom: The HK linear polarization spectrum of GRS 1915+05, Cyg X-2, Sco X-1, and the polarized standard star HD 184143. The gap in the spectra between 1.8 and 2.0 μm is the atmospheric absorption band.](image)

**TABLE 2**

**Polarimetry Results**

| Object       | UT Date   | A. 1.65 μm p (%) | θ (deg) | I (mJy) |
|--------------|-----------|------------------|--------|---------|
| Sco X-1      | 2004 July 18 | 0.38 ± 0.04     | 136 ± 2 | 21 ± 2  |
|              | 2004 July 23 | 0.93 ± 0.05     | 147 ± 3 | 15 ± 1  |
| Cyg X-2      | 2004 July 22 | 0.67 ± 0.04     | 116 ± 2 | 32 ± 2  |
|              | 2004 July 22 | 1.14 ± 0.06     | 129 ± 3 | 22 ± 2  |
| GRS 1915+105 | 2004 July 19 | 1.7 ± 0.2       | 96 ± 2  | 6.4 ± 0.4|
|              |            | 5.4 ± 0.7       | 84 ± 3  | 4.3 ± 0.2|
|              |            | 7.9 ± 1.0       | 49 ± 2  | 29 ± 3  |
|              |            | 5.0 ± 1.2       | 50 ± 3  | 15 ± 2  |

**Notes.**—The 1.65 and 2.4 μm percentage polarization (p), position angle (θ), and dereddened flux densities (I) are calculated using mean values over 0.10 μm.

![Fig. 3.—Optical and near-infrared polarization values for Sco X-1. The optical points (asterisks) are taken from Schultz et al. (2004) and our HK polarization spectrum (crosses) is shown. The dashed line is the interstellar polarization model fit to the optical.](image)

are significant (note that we average over 90 pixels) a bias correction (Simmons & Stewart 1985) is not necessary, as pointed out by Jensen et al. (2004).

4.1. Sco X-1

Sco X-1 has a color excess of E(B − V) = 0.3, so some interstellar polarization is expected. Schultz et al. (2004) fit the UBVRI optical linear polarization values with the empirical formula of Serkowski (P(λ) = P_{max} \exp^{-K'\lambda^2/λ_{max}^2}, Serkowski et al. 1975) and find λ_{max} = 596 nm and P_{max} = 0.70% (K' = 0.01 + λ_{max}/602). These values predict an interstellar polarization of 0.25% and 0.10% at 1.65 and 2.4 μm, respectively. Figure 3 shows the optical and near-infrared linear polarization values and the expected interstellar polarization. The mean linear polarization is 0.47% ± 0.05% and 1.3% ± 0.10% at 1.65 and 2.4 μm, respectively. Although the optical polarization may be described as interstellar, the H- and K-band polarization clearly cannot. The overall optical and near-infrared polarization spectrum can be described by two components: an interstellar polarization spectrum in the optical, and another component that dominates the H- and K-band polarization spectrum. It should be noted that recent broadband JK measurements of polarization of Sco X-1 agree with the values we obtain here (Russell & Fender 2007). Given that Sco X-1 is known to be a powerful and variable jet source (Fomalont et al. 2001), the component in the IR is most likely due to optically thin synchrotron emission from the jet (see § 5). We can compare the near-infrared position angles with the position angle in the radio images of Sco X-1. The mean position angle of the radio jet on the sky is 54° (Fomalont et al. 2001). This is approximately perpendicular to the near-infrared electric vector position angle, which implies that the magnetic field is aligned with the jet (assuming optically thin synchrotron emission).

4.2. Cyg X-2

Although polarization observations of Cyg X-2 are limited, optical linear measurements show Cyg X-2 to be 0.29% polarized, most of which may be intrinsic to the source (Koch Miramond &
Naylor 1995). Our IR linear polarization measurements of 1.7% and 5.4% at 1.65 and 2.4 μm, respectively, show a considerable excess in the near-infrared compared to the optical. It is clear that interstellar polarization cannot explain the observed optical and near-infrared polarization values. The optical position angle of 36° (Koch Miramond & Naylor 1995) differs from our near-infrared value; however, this can be explained if the jet evolves with time. The different position angles at 1.65 and 2.4 μm can be explained if the different bands come from different regions. For a “simple” conical jet, the jet size scales with wavelength, so a 2.4 μm jet would be (2.4/1.65) times larger than a 1.65 μm jet. Cyg X-2, like Sco X-1, is a radio source (see Migliari & Fender 2006) and a member of the “Z source” and as such is also very likely to be a jet source (although one has never been spatially resolved).

4.3. GRS 1915+105

GRS 1915+105 is a powerful relativistic jet source (Mirabel & Rodriguez 1994; Fender et al. 1999; Miller-Jones et al. 2005) and the single most convincing example of IR synchrotron emission, with IR flarelike events unambiguously associated with similar events at millimeter and radio wavelengths (e.g., Fender et al. 1997; Mirabel et al. 1998; Eikenberry et al. 1998b; Fender & Pooley 2000). However, at the time of the observations, radio monitoring with the Ryle Telescope at 15 GHz (G. Pooley 2004, private communication) indicated a low level of activity, with flux densities ≤10 mJy.

Our near-infrared linear polarization measurements of 7.5% and 5.0% at 1.65 and 2.4 μm may in fact be consistent with interstellar polarization, given the very high degree of extinction (Chapuis & Corbel 2004). However, we can estimate the maximum amount of interstellar polarization, given that there is a good correlation between the interstellar extinction and optical depth and thus polarization at 2.2 μm for field stars (Jones 1989). For GRS 1915+105 the extinction of $E(B-V) = 6.3$ (or $A_v = 19.5$ mag; Chapuis & Corbel 2004) gives an optical depth of $\tau_{2.2\mu m} \sim 1.7$ and so a maximum interstellar polarization of $p_{2.2\mu m} = 3.3%$. The observed polarization at 2.2 μm of $3.7% \pm 1.1%$ (calculated using the mean value over 0.10 μm) suggests that the observed polarization may in fact be consistent with interstellar polarization. However, if the dust-induced polarization contribution is low, then the radio jets (mean position angle of $\sim143°$; Miller-Jones et al. 2005) is perpendicular to the electric near-infrared vector position angle, implying that the magnetic field is aligned with the jet.

5. POLARIZATION FROM JETS?

In X-ray binaries significant linear polarization caused by electron scattering in an isotropic medium (e.g., the environment of the accretion flow) is expected at optical wavelengths. Indeed the linear polarization property of the microquasar GRO J1655−40 in quiescence may be explained by such a mechanism (Scaltriti et al. 1997), where the linear polarization originates from asymmetrical regions in the inner accretion disk (electron scattering of the disk radiation by the secondary star is insignificant, because the secondary stars in low-mass X-ray binaries (LMXBs) have low surface temperatures and therefore low free electron densities). In the case of the persistent LMXBs where the accretion disk dominates the optical light, the linear polarization should have a component that is produced by electron scattering by plasma above the accretion disk. Although a strong interstellar component is present, for Rayleigh and Thompson scattering processes, the level of linear polarization decreases as a function of increasing wavelength.

An excess weak component in the optical polarization is detected in Sco X-1 (Schultz et al. 2004), which is most likely due to electron scattering in the accretion disk. Similarly, for Cyg X-2 the optical polarization level has been measured to be 0.28%, which may be intrinsic to the source. However, we find the 2.4 μm linear polarization level to be considerably larger compared to the optical and so the 2.4 μm polarization cannot be explained by interstellar polarization or by electron scattering. In both of these sources, therefore, there seems to be some intrinsic polarization of the near-infrared that probably cannot be attributed to electron scattering. In the case of GRS 1915+105 the level of polarization is high, but it does show the trend expected for interstellar scattering.

An alternative possibility is that the “excess” near-infrared polarization is due to synchrotron emission from jets. Two polarization signatures are expected from the jet, depending on whether or not the synchrotron emission is optically thick or thin. Above some frequency this flat spectral component should break to an optically thin spectrum ($\alpha \sim -0.6; S_\nu \propto \nu^{-0.6}$) corresponding to the point at which the entire jet becomes transparent; i.e., emission at the break frequency arises primarily from the “base” of the jet (although this may be still physically separated from the central accretor). For the optically thick part of the spectrum, which results in the flat spectral component ($\alpha \sim 0$) observed in the hard X-ray state (Fender 2001), no more than a few percent polarization is expected. This is indeed observed for at least two hard-state black hole sources in the radio band (see Fender 2001); however, such a low level of polarization would be very hard to distinguish from the similar levels expected from scattering in an accretion disk and/or by the interstellar medium.

There exists the possibility of a large fractional polarization level from optically thin synchrotron emission. While it is by no means firmly established, a small number of observational and theoretical results suggest a break between optically thick and thin emission should occur around the near-infrared band (e.g., see Corbel & Fender 2002). Optically thick synchrotron emission has a maximum linear polarization of $\sim10%$ (Blandford et al. 2002), whereas optically thin synchrotron emission can have a fractional linear polarization as high as 70% (Blandford et al. 2002), where the observed level is generally significantly less than this due to a mixing of regions with different magnetic field orientations and/or Faraday rotations within one resolution element of the telescope. Nevertheless, some X-ray binary jets show up to $\sim30%$ polarization (Fender 2001), indicating a highly significant ordering of the magnetic field. Figure 4 illustrates in more detail our expectation for the intrinsic (i.e., before interstellar scattering) linear polarization signature in the near-infrared and optical regimes, based on spectral energy distributions published in Corbel & Fender (2002) and Homan et al. (2005) and the simple ideas outlined above about the expected polarization fraction. At long wavelengths (maybe in the mid-infrared: the break is hard to determine precisely) there will only be $\sim1%$ polarization from the self-absorbed jet; at short wavelengths a comparable level will be measured due to scattering in the accretion flow. However, in the relatively narrow spectral region in which optically thin synchrotron emission dominates, we may expect a strong signature that initially rises to longer wavelengths as the relative jet: disk fraction increases. However, it should be noted that the break from optically thick to optically thin synchrotron and the normalization of the disk component may vary from source to source, which will mean the width and peak of the high-polarization regime will vary. This is discussed in Nowak et al. (2005) for the case of black hole sources and clearly illustrated by Migliari et al. (2006) for the case of the neutron star 4U 0614+091, where the break to optically thin synchrotron appears
to occur at a lower frequency than what is measured for the black hole source GX 339−4 in Corbel & Fender (2002). Therefore, the sketch in Figure 4 can only be regarded as schematic.

Given that the 2.4 μm polarization level is greater than the 1.65 μm polarization level suggests that the most likely origin of the K-band linear polarization in Sco X-1 and Cyg X-2 is from a jet. Why the degree of polarization should be different by an order of magnitude between the two neutron star systems is unclear, but may relate to the accretion state (i.e., branch of the “Z”) the sources were in at the time (some branches seem to be more closely associated with jets than others, e.g., Migliari & Fender 2006). These observations support the recent discovery with Spitzer of optically thin synchrotron emission in the IR band from another neutron star X-ray binary, 4U 0614+091 (Migliari et al. 2006). In the case of GRS 1915+105 the result is ambiguous and further observations will be required to see how it might vary in states when the jet is more powerful (as indicated by, e.g., simultaneous radio observations).

For Sco X-1 we find that the magnetic field is aligned with the jet (see § 4.1), and the same for GRS 1915+105 if the dust-induced polarization contribution is low (see § 4.3). Both parallel and perpendicular magnetic fields are seen in radio jets. In the radio polarization maps of Cir X-1 one observes the polarization vector rotate through 90° between the core and the jet (R. Fender et al. 2007, in preparation). Parallel magnetic fields are related to the intrinsic jet structure, perhaps helping to collimate the flow, whereas perpendicular magnetic fields indicate shocks, where the outflow is compressed along the jet's axis (Saikia & Salter 1988). Measurements of the linear polarization of the compact jet in the near-infrared can probe closer to the central black hole or neutron star than the radio band, and reveal the degree or ordering of the magnetic field close to the jet’s base. Furthermore, Faraday rotation (which is proportional to $\lambda^2$) is insignificant at near-infrared wavelengths, so that the linear polarization electric vector position angle tells us directly about the orientation of the magnetic field (the two are perpendicular). The three measurements reported here, at least two of which indicate a significant contribution of synchrotron emission in the near-infrared, should be the beginning of a highly useful line of inquiry in the near future.

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REFERENCES

Bandyopadhyay, R. M., Shahbaz, T., Charles, P. A., & Naylor, T. 1999, MNRAS, 306, 417
Blandford, R., Agol, E., Broderick, A., Heyl, J., Koopmans, L., & Lee, H.-W., 2002, in Astrophysical Spectropolarimetry, ed. J. Trujillo-Bueno et al. (Cambridge: Cambridge Univ. Press), 177
Blandford, R. D., & Konigl, A. 1979, ApJ, 232, 34
Chapuis, C., & Corbel, S. 2004, A&A, 414, 659
Corbel, S., & Fender, R. P. 2002, ApJ, 573, L35
Eikenberry, S. S., Matthews, K., Murphy, T. W., Jr., Nelson, R. W., Morgan, E. H., Remillard, R. A., & Mano, M. 1998b, ApJ, 506, L31
Fender, R. P. 2001, MNRAS, 322, 31
Fender, R. P. 2006, in Compact Stellar X-Ray Sources, ed. W. H. G., Lewin & M., van der Klis (Cambridge: Cambridge Univ. Press), 381
Fender, R. P., Garrington, S. T., McKay, D. J., Muxlow, T. W. B., Pooley, G. G., Spencer, R. E., Stirling, A. M., & Wallman, E. B. 1999, MNRAS, 304, 865
Fender, R. P., & Pooley, G. G. 2000, MNRAS, 318, L1
Fender, R. P., Pooley, G. G., Brocksopp, C., & Newell, S. J. 1997, MNRAS, 290, L65
Fomalont, E. B., Geldzahler, B. J., & Bradshaw, C. F. 2001, ApJ, 553, L27
Gehrels, T., ed. 1974, Planets, Stars, and Nebulae Studied with Photo-polarimetry (Tucson: Univ. Arizona Press)
Homan, J., Buxton, M., Markoff, S., Bailyn, C. D., Nespoli, E., & Belloni, T. 2005, ApJ, 624, 295
Howarth, I. D. 1983, MNRAS, 203, 301
Jensen, E. L. N., Mathieu, R. D., Donar, A. X., & Dullighan, A. 2004, ApJ, 600, 789
Jones, T. J. 1989, ApJ, 346, 728
Koch Miramond, L., & Naylor, T. 1995, A&A, 296, 390
Lazzati, D., et al. 2003, A&A, 410, 823
Markoff, S., Falcke, H., & Fender, R. P. 2001, A&A, 372, L25
Markoff, S., Nowak, M., Corbel, S., Fender, R. P. & Falcke, H. 2003, A&A, 397, 645
Migliari, S., & Fender, R. P. 2006, MNRAS, 366, 79
Migliari, S., Tomskick, J. A., Maccarone, T. J., Gallo, E., Fender, R. P., Nelemans, G., & Russell, D. M. 2006, ApJ, 643, L41
Miller-Jones, J. C. A., McCormick, D. G., Fender, R. P., Spencer, R. E., Muxlow, T. W. B., & Pooley, G. G. 2005, MNRAS, 363, 867
Mirabel, I. F., Dhawan, V., Chaty, S., Rodriguez, L. F., Marti, J., Robinson, C. R., Swank, J., & Geballe, T. 1998, A&A, 330, L9
Mirabel, I. F., & Rodriguez, L. F. 1994, Nature, 371, 46
Nowak, M. A., Wilms, J., Heinz, S., Pooley, G., Pottschmidt, K., & Corbel, S. 2005, ApJ, 626, 1006
Orosz, J. A., & Kuulkers, E. 1999, MNRAS, 305, 132
Pacholczyk, A. G. 1977, Radio Galaxies: Radiation Transfer, Dynamics, Stability, and Evolution of a Synchrotron Plasmon (Oxford: Pergamon)
Russell, D. M., & Fender, R. P., 2007, MNRAS, submitted
Russell, D. M., Fender, R. P., Hynes, R. I., Brocksopp, C., Homan, J., Jonker, P. G., & Buxton, M. M. 2006, MNRAS, 371, 1334
Saitta, D. J., & Salter, C. J. 1985, ARA&A, 26, 93
Scaltriti, F., Bodo, G., Ghisellini, G., Gliozzi, M., & Trussoni, E. 1997, A&A, 325, L29
Schultz, J., Hakala, P., & Huovelin, J. 2004, Baltic Astron., 13, 581
Serkowski, K., Mathewson, D. L., & Ford, V. L. 1975, ApJ, 196, 261
Simmons, J. F. L., & Stewart, B. G. 1985, A&A, 142, 100
Vrtilek, S. D., Penninx, W., Raymond, J. C., Verbunt, F., Hertz, P., Wood, K., Lewin, W. H. G., & Mitsuda, K. 1991, ApJ, 376, 278