Original citation:
Miller, J. M. et al. (2006). The magnetic nature of disk accretion onto black holes. Nature, 441(7096), pp. 953-955

Permanent WRAP url:
http://wrap.warwick.ac.uk/48727

Copyright and reuse:
The Warwick Research Archive Portal (WRAP) makes the work of researchers of the University of Warwick available open access under the following conditions. Copyright © and all moral rights to the version of the paper presented here belong to the individual author(s) and/or other copyright owners. To the extent reasonable and practicable the material made available in WRAP has been checked for eligibility before being made available.

Copies of full items can be used for personal research or study, educational, or not-for-profit purposes without prior permission or charge. Provided that the authors, title and full bibliographic details are credited, a hyperlink and/or URL is given for the original metadata page and the content is not changed in any way.

Publisher's statement:
© 2012 Nature Publishing Group
DOI: 10.1038/nature04912

A note on versions:
The version presented here may differ from the published version or, version of record, if you wish to cite this item you are advised to consult the publisher's version. Please see the 'permanent WRAP url' above for details on accessing the published version and note that access may require a subscription.

For more information, please contact the WRAP Team at: wrap@warwick.ac.uk

warwickpublicationswrap

highlight your research

http://go.warwick.ac.uk/lib-publications

The magnetic nature of disk accretion onto black holes

Jon M. Miller[1], John Raymond[2], Andy Fabian[3], Danny Steeghs[2], Jeroen Homan[4],
Chris Reynolds[5], Michiel van der Klis[6], Rudy Wijnands[6]

[1] *University of Michigan Department of Astronomy, 500 Church Street, Ann Arbor, MI 48109, USA*

[2] *Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA, 02138 USA*

[3] *University of Cambridge Institute of Astronomy, Cambridge CB3 OHA, UK*

[4] *Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA*

[5] *University of Maryland Department of Astronomy, College Park, MD 20742, USA*

[6] *Astronomical Inst. Anton Pannekoek, Univ. of Amsterdam, Kruislaan 403, 1098 SJ Amsterdam, NL*

Although disk accretion onto compact objects - white dwarfs, neutron stars, and black holes - is central to much of high energy astrophysics, the mechanisms which enable this process have remained observationally elusive. Accretion disks must transfer angular momentum for matter to travel radially inward onto the compact object[1]. Internal viscosity from magnetic processes[1,2,3,4] and disk winds[5] can in principle both transfer angular momentum, but hitherto we lacked evidence that either occurs. Here we report that an X-ray-absorbing wind discovered in an observation of the stellar-mass black hole binary GRO J1655$-$40[6] must be powered by a magnetic process that can also drive accretion through the disk. Detailed spectral analysis and modeling of the wind shows that it can only be powered by pressure generated by magnetic viscosity internal to the disk or magnetocentrifugal forces. This result demonstrates that disk accretion onto black holes is a fundamentally magnetic process.

To study the nature of disk accretion onto black holes, we observed the transient source GRO J1655-40 with the Chandra X-ray Observatory for 63.5 ksec starting on 1 April 2005 at 12:41:44 (TT), during an X-ray bright phase of its 2005 outburst. GRO J1655$-$40 is a binary system at a distance of 3.2 kpc that harbors a black hole with a mass of $7.0~\mathrm{M}_\odot$, which accretes from an F3 IV – F6 IV star with a mass of $2.3~\mathrm{M}_\odot$ in a 2.6-day orbit[6]. The inner disk is viewed at an inclination of 67–85° (nearly edge-on)[6,7]. Using Chandra, we obtained a robust high resolution X-ray spectrum of GRO J1655$-$40 in the soft X-ray band (see Figure 1).

It is common to decompose the broad-band spectra of stellar-mass black holes into disk blackbody and power-law components. Assuming the standard equivalent neutral hydrogen absorption[10] along the line of sight to GRO J1655$-$40 ($N_H = 7.4 \times 10^{21}~\mathrm{atoms~cm^{-2}}$), this spectral model gives a disk temperature of $kT = 1.34(1)$ keV and a photon power-law index of $\Gamma = 3.54(1)$ in the 1.2–19 Å range, and a total flux of $4.70(5) \times 10^{-8}~\mathrm{erg~cm^{-2}~s^{-1}}$ (unabsorbed). This flux implies a luminosity of $L = 3.3 \times 10^{37}~\mathrm{erg~s^{-1}}$ for $d = 3.2$ kpc, or 4% of the Eddington limit for a 7 $\mathrm{M}_\odot$ black hole. The disk contributes 65% of the unabsorbed flux.

The HETGS spectra of GRO J1655$-$40 contain 90 absorption lines significant at the 5σ level of confidence or higher. We can confidently identify 76 of these lines with resonance lines expected from over 32 charge states. The properties of these lines were measured with simple Gaussian line functions and local continuum models. Line centroid wavelengths and oscillator strengths were taken from a set of standard references[11,12,13]. Two findings demand that the absorption arises in a disk–driven wind. First, the lines show blue-shifts in the 300–1600 $\mathrm{km~s^{-1}}$ range, indicating a flow into our line of sight (see Figure 1, Figure 2, and the Supplementary Information). Second, the spectra contain no strong emission lines; this fact signals that the absorbing gas is mostly equatorial along the plane of the disk.

To better understand the nature of the wind, we constructed a number of photoionized plasma models based on the methodology and atomic physics packages described in a prior work[14,8]. (The models used in this work differ only in that new dielectronic recombination rates for Fe and Ni were used to more accurately describe L-shell ions[15].) These models describe a gas in photoionization equilibrium, with heating by photoionization and Compton scattering and cooling by line and continuum emission and Compton scattering. The predicted ionization state of the gas is combined with a curve of growth[16] for a chosen velocity width to determine line equivalent widths using Voigt profiles. The code accounts for line blends self-consistently. A standard set of elemental abundances are used in the code[17]. The illuminating spectrum is taken to be the composite thermal and non-thermal continuum spectrum described briefly above.

The observed spectrum is consistent with absorption in a constant-density slab with a thickness of approximately 2.5×10^8 cm and a number density of $n = 5.6 \times 10^{15}$ atoms cm^{-3} at a mean distance of 4.8×10^8 cm from the black hole. This translates to approximately $200\ R_{Schw.}$ (where $R_{Schw.} = 2GM/c^2$); the component of the wind velocity in our line of sight is much slower than the local virial velocity. The temperature of the gas is 0.2–1.0$\times 10^6$ K. An intrinsic FWHM of 300 km s^{-1} matches the observed lines which are not saturated (see Figure 2 and the Supplementary Information). An important feature of this wind is that it is highly ionized:

$\log(\xi) = \log(L_X/nr^2) =$ 4.2–4.7 (where ξ is the ionization parameter, L_X is X-ray luminosity, n is density, and r is the radius from the ionizing source).

The data permit strong independent constraints on the geometry and extent of the wind absorption. An inner radial extent of $10^{7.5}$ cm is set by the density at which Fe XXIII lines are produced. At smaller radii, the ionization parameter requires a density so large that the metastable 2s2p^{3}P level of Fe XXIII would be populated, producing lines that are not observed. An outer radial extent of $10^{9.5}$ cm is set by dilution and line ratios. At larger radii, the thickness of the absorbing gas becomes large compared to the distance, so $1/r^2$ dilution of the radiation field makes it impossible to get enough total column at high enough ionization parameter. A lower limit of 6° on the height of the gas above the disk midplane comes from the fact the line of sight must pass over the outer edge of the disk[18]. An upper limit on the vertical extent comes from the lack of emission features. A Monte Carlo simulation for a cascade resulting from absorption in the 2s-4p line of Fe XXIV predicts a 2p-3s emission line with equivalent width $0.65 \times 28\Omega/4\pi = 18\Omega/4\pi$ mÅ (where Ω is the solid angle covering factor). An upper limit of a 2mÅ to such a feature implies an upper limit of about 12° to the vertical extent of the absorbing gas.

The properties of thermally–driven winds have been studied, especially within the context of outer accretion disks being illuminated by a central X-ray source[19]. In such cases, it is possible to define a critical radius $R_C = (1.0 \times 10^{10}) \times (M_{BH}/M_{\odot})/(T_{C8})$ cm, and a wind may occur for any $R/R_C > 0.1$ (where T_{C8} is the gas temperature in units of 10^8 K). Based on temperatures derived from our photoionization models, the smallest possible value of R_C for the wind observed in

GRO J1655$-$40 is 7×10^{12} cm. Thus, the minimum radius at which a disk wind can be thermally driven is approximately two orders of magnitude greater than is plausible in GRO J1655$-$40. Similar results are obtained when our results are compared to new models for the winds in AGN such as NGC 3783[20].

The wind observed is too highly ionized to be driven by radiation pressure. The overwhelming majority of absorption lines observed are from He-like and H-like species, which means that there is little UV opacity in the wind by which momentum may be transferred. At ionization parameters of $\xi > 10^3$, models for line–driven winds in AGN indicate that UV emission lines provide no additional driving force[21]. Moreover, our photoionization code measures radiation pressure as the momentum of the photons absorbed, which is comparable to the electron scattering radiation pressure, and even together these effects fall far short of producing the observed momentum flux in the wind.

Given that thermal and radiative driving fail by orders of magnitude, magnetic driving of the wind in GRO J1655$-$40 is the only plausible mechanism remaining. Our model implies a mass loss rate in the wind of $\dot{m}_w = 3.5 \times 10^{17}$ g/s or approximately 0.5 g/cm^2/s. For a typical blue-shift of 500 km/s, this translates into a kinetic energy flux of 6.3×10^{14} erg/cm^2/s. An angle of 9° above the disk midplane at radius of 4.8×10^8 cm from the black hole corresponds to a height of $Z = 0.15r$; an energy flux of 2.0×10^{16} erg/cm^2/s is required to lift the gas to that height. The luminosity of the central engine as derived from fits to the continuum implies a mass accretion rate of $\dot{m}_a = 3.7 \times 10^{17}$ g/s for an accretion efficiency of 10%. The viscous energy flux dissipated is given by $3GM_{bh}\dot{m}_a/4\pi r^3 = 2.3 \times 10^{18}$ erg/cm^2/s. Recent simulations show that the magnetorotational instability[2,3,4] can not only drive turbulence, viscosity, and accretion through a disk, but can transmit 25% of the magnetic energy flux vertically out of the disk[22] and drive a wind. In the case of GRO J1655$-$40, 25% of the viscous energy flux is comparable to the flux required to drive the wind to infinity. The wind outflow velocity and mass outflow rate are remarkably similar to predictions resulting from from simulations of magnetically–driven winds from MRI disks[24].

It is also possible that the wind is driven by magnetocentrifugal forces[5]. The absorption spectrum contains no information about velocities tangential to our line of sight. Theoretical models show that largely equatorial winds can arise via magnetocentrifugal driving when the magnetic field vector makes a small angle to the disk plane[23]; however, recent simulations suggest that it is difficult to maintain the poloidal magnetic field required in a wind with a large mass outflow[24]. Given that the wind arises in a disk which is almost certainly Keplerian, however, magnetocentrifugal driving cannot be discounted. The winds in some young stars (FU Orionis class) are driven by magnetocentrifugal forces[25]. Tapping into the rotational velocity of the disk would help to expel the wind to infinity. Although internal magnetic viscosity and magnetic winds are sometimes posited as complete and separate processes, the most physically realistic scenario may be one in which both processes act to drive disk accretion and outflows.

Winds are commonly observed in accreting compact objects; however, GRO J1655$-$40 is the first case wherein it is clear that the wind must be launched from the disk (not the companion star) and must be driven primarily by magnetic processes (not thermal and radiative pressure).

An X-ray wind with some similarities to those in AGN was detected in the accreting neutron star binary Circinus X-1[26]; however, in Circinus X-1 contributions from a massive companion star cannot be ruled out, and the wind can be driven by thermal and radiation pressure[26]. A wind more certainly tied to the disk was detected in the black hole binary GX 339$-$4, but too few lines were detected to constrain the driving mechanism[8]. Though radiative driving may be important in most white dwarf systems, there is at least one system where it may be inadequate[27]. Similarly, theoretical considerations suggest that magnetocentrifugal forces are important in AGN winds[28,29], but present data do not yet require or rule out these effects. Our results therefore represent a rare and crucial insight into the nature of the processes which drive disk accretion in black holes. Magnetic pressure supplied by the disk provides a natural means of driving the highly ionized winds observed in many accreting stellar-mas black holes and neutron stars, and may play a role in driving the hottest winds observed in AGN. Indeed, winds and jets are ubiquitous features in accretion-powered astrophysics, and the role of magnetic processes revealed in GRO J1655$-$40 gives a broad observational insight into the physical coupling between inflows and outflows in accreting compact objects.

1. Shakura, N. I., Sunyaev, R. A., Balck holes in binary systems. Observational Appearance. *Astron. Astrophys.*, **24**, 337-355 (1973).

2. Balbus, S. A., Hawley, J. F., A powerful local shear instability in weakly magnetized disks. *Astrophys. J.*, **376**, 214-233 (1991).

3. Hawley, J. F., Gammie, C. F., Balbus, S. A., Local Three-dimensional Magnetohydrodynamic

Solutions of Accretion Disks. *Astrophys. J.*, **440**, 742-763 (1995).

4. Balbus, S. A., Hawley, J. F., Instability, turbulence, and enhanced transport in accretion disks. *Rev. Mod. Phys.*, **70**, 1-53 (1998).

5. Blandford, R. D.,Payne, D. G, Hydromagnetic flows from accretion disks and the production of radio jets. *Mon. Not. R. Astron. Soc.*, **199**, 883-903 (1982).

6. Orosz, J., Bailyn, C. D., Optical Observations of GRO J1655−40 in Quiescence. I. A Precise Mass for the Black Hole Primary. *Astrophys. J.*, **477**, 876-896 (1997).

7. Hjellming, R. M., Rupen, M. P., episodic ejection of relativistic jets by the X-ray transient GRO J1655−40, *Nature*, **375**, 464-468 (1995).

8. Miller, J. M., et al., Chandra/HETGS Spectroscopy of the Galactic Black Hole GX 399−4: A Relativistic Iron Emission Line and Evidence for a Seyfert-like Warm Absorber. Astrophys. J., **601**, 450-465 (2004).

9. Houck, J. C., Denicola, L. A., ISIS: An Interactive Spectral interpretation System for High Resolution X-ray Spectroscopy. *Astronomical Data Analysis Softweare and Systems IX, Astronomical Society of the Pacific Conference Proceedings*, **216**, 591-594 (2000).

10. Dickey, J. M., Lockman, F. J., H I in the Galaxy. *Annu. Rev. Astron. Astrophys.*, **28**, 215-261 (1990).

11. Verner, D. A., Verner, E. M., Ferland, G. J., Atomic Data for Permitted Resonance Lines of Atoms and Ions from H to Si, and S, Ar, Ca, and Fe. *Atomic Data and Nuclear Data Tables,* **64**, 1 (1996).

12. The National Institute of of Standards and Technology (NIST) Atomic Spectra Database, Standard Reference Database 78, available on-line at http:physics.nist.govcgi-binAtDatamain_asd (2005).

13. Nahar, S., Pradhan, A. K., Atomic data from the Iron Project. XXXV. Relativistic fine structure oscillator strengths for Fe XXIV and Fe XXV. *Astron. Astrophs. Suppl.*, **135**, 347-357 (1999).

14. Raymond, J., A model of an X-ray-illuminated accretion disk and corona. *Astrophys. J.*, **412**, 267-277 (1993).

15. Colgan, J., Pindzola, M. S., Badnell, N. R., Dielectronic recombination data for dynamic finite-density plasmas. V: the lithium isoelectronic sequence. *Astron. Astrophys*, **417**, 1183-1188 (2004).

16. Spitzer, L., *Physical Processes in the Interstellar Medium*. New York: Wiley (1978).

17. Grevesse, N., & Sauval, A. J., in *Solar Composition and its Evolution – from Core to Corona*, ed. C. Frölich, M. C. E. Huber, S. K. Solanski, & r. von Steiger, (Dordrecht: Kluwer), 161 (1998).

18. Vrtilek, S., et al., Observations of Cygnus X-2 with IUE - Ultraviolet results from a multiwavelength campaign. *Astron. Astrophys.*, **234**, 162-173 (1990).

19. Begelman, M. C., McKee, Shields, G. S., Compton heated winds and coronae above accretion disks. II Dynamics. *Astrophys. J.*, **271**, 70-89 (1983).

20. Chelouche, D., Netzer, H., Dynamical and Spectral Modeling of the Ionized Gas and Nuclear Environment in NGC 3783. *Astrophys. J.*, **625**, 95-107 (2005).

21. Proga, D., Stone, J. M., Kallman, T. R., Dynamics of Line-Driven winds in Active Galactic Nuclei. *Astrophys. J.*, **543**, 686-696 (2000).

22. Miller, K. A., Stone, J. M., The Formation and Structure of a Strongly Magnetized Corona above a Weakly Magnetized Accretion Disk. *Astrophys. J.*, **534**, 398-419 (2000).

23. Spruit, H. C., in "Physical Processes in Binary Stars", eds. R. A. M. J. Wijers, M. B. Davies, and C. A. Tout, Kluwer Dordrecht (NATO ASI series) (1996).

24. Proga, D., Numerical Simulations of Mass Outflows Driven from Accretion Disks by Radiation and Magnetic Forces. *Astrophys. J.*, **585**, 406-417 (2003).

25. Calvet, N., Hartmann, L., Kenyon, S. J., Mass loss from pre-main-sequence accretion disks. I - The accelerating wind of FU Orionis. *Astrophys. J.*, **402**, 623-634 (1993).

26. Schulz, N. S., Brandt, W. N., Variability of the X-ray P Cygni Line Profiles from Cicinus X-1 Near Zero Phase". *Astrophys. J.*, **572**, 972-983 (2002).

27. Mauche, C. W., & Raymond, J. C., Extreme Ultraviolet Explorer Observations of OY Carinae in Superoutburst. *Astrophys. J.*, **541**, 924-936 (2000).

28. Konigl, A., Kartje, J. F., Disk-Driven Hydromagnetic Winds as a Key Ingredient of Active Galactic Nuclei Unification Schemes. *Astrophys. J.,* **434**, 446-467 (1994).

29. Everett, J. E., Radiative Transfer and Acceleration in Magnetocentrifugal Winds. *Astrophys. J.,* **631**, 689-706 (2005).

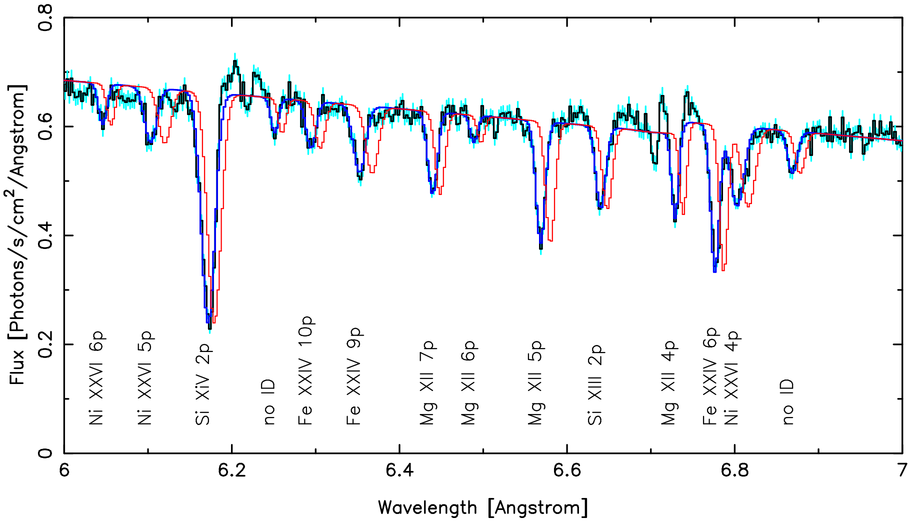
Correspondence and requests for materials should be addressed to J.M.M. (jonmm@umich.edu)

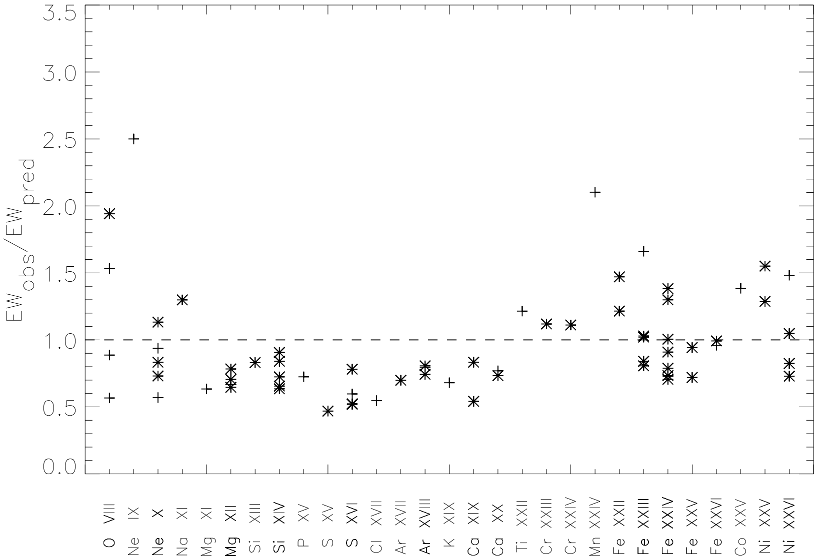
We acknowledge insightful conversations with Nuria Calvet, Lee Hartmann, Daniel Proga, and Michael Rupen. We are indebted to Andrea Prestwich, Harvey Tananbaum, and the Chandra staff for its help in making this observation possible. We thank Leslie Sage and Beth Lauritsen for editorial insights. This work was supported by funding from NASA through the Chandra guest obsever program (to J. M. M.).

Figure 1. The slice of the disk wind spectrum observed in GRO J1655$-$40 with Chandra. In the plot above, the best-fit phenomenological model is shown in blue. The model in red plots the natural line wavelengths, to illustrate that the observed absorption is blue-shifted. The errors shown are 1σ statistical errors on the photon flux. To obtain this high resolution spectrum, the Chandra High Energy Transmission Grating Spectrometer (HETGS) was used to disperse the X-ray flux onto the Advanced CCD Imaging Spectrometer (ACIS), which was operated in "continuous-clocking" mode. The data reduction and preparation was performed using the latest version of the standard Chandra packages ("CIAO"), and a procedure typical for this instrumental configuration[8]. The spectra presented in this work were produced by adding the first-order spectra from the HETGS medium energy grating (MEG) at a resolution of 0.005 Å per bin, and the first-order spectra from the high energy grating (HEG) at a resolution of 0.0025 Å per bin. The HEG spectrum was used to characterize the 1–11Å band, and the MEG spectrum was used to characterize the 11–19Å band. The continuum emission was characterized using the HEG spectrum. All spectral fits were made using the ISIS[9] spectral fitting package.

Figure 2. Comparison of the best model for the disk wind in GRO J1655$-$40 to the data. The plot above shows the ratio of the absorption line equivalent widths measured in GRO J1655$-$40, to the equivalent widths predicted by the photoizonization model which best describes the disk wind. The model assumes an internal velocity widths of 300 km/s. Revised solar abundances[17] are adequate to describe the elements between Na and K (inclusive). Abundances of twice the revised solar value are required to describe the lines observed rom other elements. The full spectrum of GRO J1655$-$40 and the measured properties of the absorption lines are detailed in the

Supplemental Information.


Flux [Photons/s/cm^2/Angstrom]
Wavelength [Angstrom]
0
0.2
0.4
0.6
0.8
6
6.2
6.4
6.6
6.8
7
Ni XXVI 6p
Ni XXVI 5p
Si XiV 2p
no ID
Fe XXIV 10p
Fe XXIV 9p
Mg XII 7p
Mg XII 6p
Mg XII 5p
Si XIII 2p
Mg XII 4p
Fe XXIV 6p
Ni XXVI 4p
no ID


EW_obs/EW_pred
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
O VIII
Ne IX
Ne X
Na XI
Mg XI
Mg XII
Si XIII
Si XIV
P XV
S XV
S XVI
Cl XVII
Ar XVII
Ar XVIII
K XIX
Ca XIX
Ca XX
Ti XXII
Cr XXIII
Cr XXIV
Mn XXIV
Fe XXII
Fe XXIII
Fe XXIV
Fe XXV
Fe XXVI
Co XXV
Ni XXV
Ni XXVI