A strong magnetic field in the jet base of a supermassive black hole

This document has been downloaded from Chalmers Publication Library (CPL). It is the author’s version of a work that was accepted for publication in:

Science (ISSN: 0036-8075)

Citation for the published paper:

http://dx.doi.org/10.1126/science.aaa1784

Downloaded from: http://publications.lib.chalmers.se/publication/218253

Notice: Changes introduced as a result of publishing processes such as copy-editing and formatting may not be reflected in this document. For a definitive version of this work, please refer to the published source. Please note that access to the published version might require a subscription.
ACKNOWLEDGMENTS

We thank G. Birngr, J. Repp, and A. J. Weymouth for discussions and the Deutsche Forschungsgemeinschaft for funding under Graduiertenkolleg 1570 and Sonderforschungsbereich 689, as well as M. Grifoni (speaker of GRK) and D. Weiss (speaker of SFB) for support. F.J.G. thanks A. Heinrich for hosting several visits at the IBM Almaden Research Center from 2005 until 2010, where first attempts to resolve metallic adatoms with subatomic resolution were performed together with C. Lutz, C. Hirihebehedin, and M. Ternes. Author contributions: M.E. performed most of the measurements and data analysis, constructed the low-temperature scan head, and prepared most figures; F.H. optimized the electronics and performed crucial measurements; J.W. performed measurements on Cu adatoms on Cu(111); H.T. and F.P. performed measurements on Cu/Cu(110) and inverse measurements using CO/Cu(111) to characterize Cu and Fe tips; M.S. constructed most of the vacuum system and sample-preparation facilities; D.M. performed the AFM measurements on Si; D.K., S.P., S.M., and H.E. performed the DFT calculations; and F.J.G. initiated and directed the project, employed the STM model, and wrote the manuscript.

SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/348/6232/308/suppl/DC1

Materials and Methods

Supplementary Text

Figs. S1 to S13

References (41–47)

19 December 2014; accepted 20 February 2015

Published online 19 March 2015

10.1126/science.aaa5329

A strong magnetic field in the jet base of a supermassive black hole

Ivan Martí-Vidal,* Sébastien Muller, Wouter Vlemmings, Cathy Horellou, Susanne Aalto

Active galactic nuclei (AGN) host some of the most energetic phenomena in the universe. AGN are thought to be powered by accretion of matter onto a rotating disk that surrounds a supermassive black hole. Jet streams can be boosted in energy near the event horizon of the black hole, and then flow outward along the rotation axis of the disk. The mechanism that forms such a jet and guides it over scales from a few light-days up to millions of light-years remains uncertain, but magnetic fields are thought to play a critical role. Using the Atacama Large Millimeter/submillimeter Array (ALMA), we have detected a polarization signal (Faraday rotation) related to the strong magnetic field at the jet base of a distant AGN, PKS 1830–211. The amount of Faraday rotation (rotation measure) is proportional to the integral of the magnetic field strength along the line of sight times the density of electrons. The high rotation measure derived suggests magnetic fields of at least tens of Gauss (and possibly considerably higher) on scales of the order of light-days (0.01 parsec) from the black hole.

Department of Earth and Space Sciences, Chalmers University of Technology, Onsala Space Observatory, SE-43990, Onsala, Sweden.

*Corresponding author. E-mail: mivan@chalmers.se
from view. These results are thus fundamental to better understand the role of magnetic fields in the AGN accretion and jet production, which are intimately related to the growth and evolution of supermassive black holes.

This detection has been possible thanks to the high resolution (sub-arcsec) of our observations with ALMA and to the use of a new differential polarimetry technique, which we briefly describe in the following lines (see supplementary text section 1).

The ALMA receivers detect the signal in two orthogonal linear polarizations, X and Y, where X is received from a horizontal dipole and Y from a vertical dipole in the frame of the antenna mount. The two lensed images of PKS 1830–211, which we call northeast (NE, upper-left in projection on sky) and southwest (SW, lower-right), are separated by 1". In Fig. 1, we show an example of snapshot images in XX and YY of the two components of the gravitational lens, as well as their difference. The difference image contains information about the difference between NE and SW in Stokes parameters Q and U. Our analysis makes use of the polarization ratio, $R_{pol}$, which is defined as

$$R_{pol} = \frac{1}{2} \left( \frac{R_{12}^{XX}}{R_{12}^{YY}} - 1 \right)$$

where $R_{12}^{XX}$ and $R_{12}^{YY}$ are the flux-density ratios between the two lensed images of the AGN, obtained separately from the XX and YY polarization products. $R_{pol}$ is a function of the parallactic angle of the antennas, $\psi$, and the observing wavelength, $\lambda$, and encodes information about the difference of polarization between the two images, via the approximately constant parameters $p_{dif}$ and $\alpha$ (supplementary text section 1), as well as their rotation measure $RM$.

$$R_{pol} = p_{dif} \cos(2\psi^0) + 2RM(\lambda^2 - \psi/RM)$$

where $\psi^0$ is the position angle of the polarization of image 1 at zero wavelength in the plane of the sky. The technique of differential polarimetry essentially enables estimation of $RM$ via fitting the observed sinusoidal dependence of $R_{pol}$ as a function of $\lambda^2$ and $\psi$, using Eq. 1.

Our results are based on ALMA observations at sky frequencies around 100, 250, and 300 GHz (8). Correcting for the cosmological redshift, these frequencies correspond to 350, 875, and 1050 GHz.
in the frame of the source. More details on these observations, and a summary of the main goals of this ALMA project, can be found elsewhere (9). We also summarize all the observations in the supplementary text (section 2). Our observations can be divided in two data sets, one consisting of six epochs in 2012 (9 April to 16 June) and the other of nine epochs in 2014 (3 May to 27 August).

In Fig. 2, we show the measured \( R_{\text{pol}} \) between the two lensed images of PKS 1830–211. These measurements have been obtained from the \( R_{\text{CX}} \) and \( R_{\text{TV}} \) values fitted with the visibility-modeling software presented in (10). The uncertainties have been obtained with the standard error propagation approach, using the uncertainties in \( R_{\text{CX}} \) and \( R_{\text{TV}} \) that were derived from the covariance matrix of the visibility fitting, as described in (10).

The derivatives of \( R_{\text{pol}} \) versus \( \lambda^2 \), which are related to \( RM \) (supplementary text section 1.3), are clearly different for different wavelength ranges. Between \( \lambda^2 = 8 \) and 12 mm\(^2\), the maximum derivative is \( 4.4 \times 10^{-3} \) mm\(^2\) rad\(^{-1}\), whereas between 0.8 and 1.6 mm\(^2\) it is \( 7 \times 10^{-3} \) mm\(^2\) rad\(^{-1}\). Because the maximum observed \( R_{\text{pol}} \) ratios are, in absolute value, similar at all wavelengths, the different derivatives of \( R_{\text{pol}} \) versus \( \lambda^2 \) must be due to larger \( RM \) at shorter wavelengths (see supplementary text section 1.3 for a more detailed discussion). Large variations of \( RM \) with wavelength have been reported in other AGN (10), although at much longer wavelengths (cm), related to larger spatial scales in the jets. Our finding cannot be explained easily if the \( RM \) is only caused by an external (e.g., spherically symmetric) screen of material being accreted onto the black hole [as in the case of the \( RM \) detected in the Galactic center (5)] and/or by external clouds. The size of the submm emitting region (estimated as the distance to the black hole at which the submm intensity is maximum) is only of the order of 0.01 pc (8). Hence, if the Faraday screen were extended and located far from the jet base, the rotation measure at submm wavelengths should not depend on the observing frequency, because the extent of the Faraday screen would be similar for all the submm jet emission. The Faraday screen must thus be close to the jet base and change substantially on sub-parsec scales (Fig. 3).

An increase of the \( RM \) at shorter wavelengths would then be explained naturally as an increase of the magnetic field strength and/or electron density as we approach the black hole. Indeed, observations of other AGN at long wavelengths (cm) show changes of \( RM \) across the jets, both longitudinal and transversal (12–14), that have been attributed to changes in particle density and magnetic fields in the jets, independent of a more distant external medium.

We have three sets of observing epochs at 250 and 300 GHz separated by a short time interval (1 to 2 days). In these three cases, we can directly estimate \( RM \) and \( p_{\text{dif}} \) by fitting \( R_{\text{pol}} \) to the model given by Eq. 1. The parameter estimates in these three data sets have been performed by least-squares minimization, comparing the measured \( R_{\text{pol}} \) to the model predictions. The data at our lowest-frequency band (i.e., 100 GHz) have been discarded from the fit, because they trace different rotation measures from different regions of the jet, as we have already discussed. We show the fitting results in Fig. 4 and the estimated parameters in Table 1. Our estimated source–rest-frame \( RM \)s are about two orders of magnitude higher than the highest values reported previously for other AGN, which are \( -10^5 \) rad/m\(^2\) (4, 6).

Although the two \( RM \) measurements in 2012 are compatible, the estimate in 2014 is higher by more than a factor of 2. Regarding the amplitude of \( R_{\text{pol}} \), which is related to the fractional polarization and to the relative polarization angles among the NE and SW images, we find different values for the two observations in 2012. These two observations were serendipitously taken before and after a strong \( \gamma \)-ray flare, which had a very weak radio counterpart (8). This leads us to speculate that the change in polarization may be correlated to the radio counterpart of that flare. Another \( \gamma \)-ray flare was detected in 2014 (15), also coincident with the time range of our 2014 observations. The new flare had a strong radio counterpart, which may also be related to the higher \( RM \) that we measure in 2014. The high variability in \( RM \) and \( p_{\text{dif}} \), in connection to the \( \gamma \)-ray flaring events, points toward a coplanar origin of the \( \gamma \)-ray emission and the 250- to 300-GHz rotation measures, hence favoring our interpretation of the \( RM \) being caused at the region very close to the jet base.

**Fig. 3. Sketch of the jet launch/acceleration region in PKS 1830–211 (not to scale).** Emission at higher frequencies comes from material closer to the black hole, at subparsec scales. At these frequencies, the main contribution to \( RM \) must come from a zone close to the jet, in order to explain the different \( RM \) values between 350 GHz and 0.8 to 1 THz (source frame).

**Fig. 4. Fits of our three epochs with quasi-simultaneous observations at 250 and 300 GHz to the model given in Eq. 1.** We show \( R_{\text{pol}} \) versus \( \lambda^2 \) corrected by \(-\psi/RM\), to obtain a sinusoidal behavior.

**Table 1. Best-fit polarization values for the three epochs with quasi-simultaneous observations at 250 and 300 GHz.** \( RM_{\text{obs}} \) are the rotation measures in the observer’s frame and \( RM_{\text{true}} \) are the rotation measures in the rest frame of the source. \( RM_{\text{true}} \) is \((1+2\gamma)^2\) times larger than \( RM_{\text{obs}} \).

<table>
<thead>
<tr>
<th>Epoch</th>
<th>10 April 2012</th>
<th>23 May 2012</th>
<th>5 May 2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>( RM_{\text{obs}} ) (10^6 rad/m²)</td>
<td>( 9.0 \pm 0.3 )</td>
<td>( 9.4 \pm 0.4 )</td>
<td>( 25.3 \pm 0.8 )</td>
</tr>
<tr>
<td>( RM_{\text{true}} ) (10^7 rad/m²)</td>
<td>( 11 \pm 0.4 )</td>
<td>( 11.5 \pm 0.5 )</td>
<td>( 31.2 \pm 1.0 )</td>
</tr>
<tr>
<td>( p_{\text{dif}} ) (10^3)</td>
<td>( 12.6 \pm 0.4 )</td>
<td>( 3.8 \pm 0.3 )</td>
<td>( 3.5 \pm 0.3 )</td>
</tr>
<tr>
<td>( 2\theta_0 – \alpha ) (deg)</td>
<td>( 59 \pm 27 )</td>
<td>( 40 \pm 23 )</td>
<td>( 25 \pm 20 )</td>
</tr>
</tbody>
</table>
Evidence for mature bulges and an inside-out quenching phase 3 billion years after the Big Bang

S. Tacchella,1*, C. M. Carollo,1† A. Renzini,2 N. M. Förster Schreiber,3 P. Lang,3 S. Wuyts,3 G. Cresci,4 A. Dekel,5 R. Genzel,6,7 S. J. Lilly,1 C. Mancini,8 S. Newman,6 M. Onodera,1 A. Shapley,6 L. Tacconi,3 J. Woo,1 G. Zamorani9

Most present-day galaxies with stellar masses \( \geq 10^{10} \) solar masses show no ongoing star formation and are dense spheroids. Ten billion years ago, similarly massive galaxies were typically forming stars at rates of hundreds solar masses per year. It is debated how star formation ceased, on which time scales, and how this “quenching” relates to the emergence of dense spheroids. We measured stellar mass and star-formation rate surface density distributions in star-forming galaxies at redshift 2.2 with \( -1 \) kiloparsec resolution. We find that, in the most massive galaxies, star formation is quenched from the inside out, on time scales less than 1 billion years in the inner regions, up to a few billion years in the outer disks. These galaxies sustain high star-formation activity at large radii, while hosting fully grown and already quenched bulges in their cores.

A t the epoch when star-formation activity peaks in the universe (redshift \( z \approx 2 \) (1, 2)), massive galaxies typically lie on the so-called “star-forming main sequence.” Their star-formation rates (SFRs) tightly correlate with the mass in stars (stellar mass \( M \)), reaching up to several hundred solar masses (\( M_\odot \)) per year and producing a characteristic specific SFR (sSFR = SFR/\( M \)) that declines only weakly with mass (3, 4). In contrast, at the present epoch, such massive galaxies are spheroids with old stellar populations, which reach central surface stellar densities well above \( 10^{10} M_\odot \) kpc\(^{-2} \) and host virtually no ongoing star formation. Although the most massive ellipticals at \( z = 0 \) bear the clear signatures of a gas-poor formation process (5, 6), the more typical population, at a mass scale of \( M \approx 10^{11} M_\odot \), consists of fast rotators (7) with disk-like isophotes (8), steep nuclear light profiles (9), and steep metallicity gradients (10), all features that indicate a gas-rich formation process.

The full cessation of star-formation activity in these typical massive galaxies (here referred to as the quenching process) is not well understood, nor is its relation with the emergence of their spheroidal morphologies. Several quenching mechanisms have been proposed. The so-called halo-quenching scenario predicts that circumgalactic gas is shock-heated to high temperatures and

**REFERENCES AND NOTES**


**ACKNOWLEDGMENTS**

This paper makes use of the following ALMA data: ADS/JAO.ALMA#2011.0.00405.S, ADS/JAO.ALMA#2012.1.00056.S.

**SUPPLEMENTARY MATERIALS**

www.sciencemag.org/content/348/6232/311/suppl/DC1

**SUPPORTING MATERIALS**

Figs. S1 to S4

Tables S1 to S3

Reference (19)

28 October 2014; accepted 12 March 2015

10.1126/science.aaa1784

**SCIENCE**
A strong magnetic field in the jet base of a supermassive black hole
Ivan Martí-Vidal et al.
Science 348, 311 (2015);
DOI: 10.1126/science.aaa1784

This copy is for your personal, non-commercial use only.

If you wish to distribute this article to others, you can order high-quality copies for your colleagues, clients, or customers by clicking here.

Permission to republish or repurpose articles or portions of articles can be obtained by following the guidelines here.

The following resources related to this article are available online at www.sciencemag.org (this information is current as of November 13, 2015):

Updated information and services, including high-resolution figures, can be found in the online version of this article at:
http://www.sciencemag.org/content/348/6232/311.full.html

Supporting Online Material can be found at:
http://www.sciencemag.org/content/suppl/2015/04/15/348.6232.311.DC1.html

This article cites 18 articles, 5 of which can be accessed free:
http://www.sciencemag.org/content/348/6232/311.full.html#ref-list-1

This article appears in the following subject collections:
Astronomy
http://www.sciencemag.org/cgi/collection/astronomy