Small-scale filament eruptions as the driver of X-ray jets in solar coronal holes

Alphonse C. Sterling1, Ronald L. Moore1,2, David A. Falconer1,2 & Mitzi Adams3

Solar X-ray jets are thought to be made by a burst of reconnection of closed magnetic field at the base of a jet with ambient open field1–2. In the accepted version of the ‘emerging-flux’ model, such a reconnection occurs at a plasma current sheet between the open field and the emerging closed field, and also forms a localized X-ray brightening that is usually observed at the edge of the jet’s base3–5. Here we report high-resolution X-ray and extreme-ultraviolet observations of 20 randomly selected X-ray jets that form in coronal holes at the Sun’s poles. In each jet, contrary to the emerging-flux model, a miniature version of the filament eruptions that initiate coronal mass ejections4–7 drives the jet-producing reconnection. The X-ray bright point occurs by reconnection of the ‘legs’ of the minifilament-carrying erupting closed field, analogous to the formation of solar flares in larger-scale eruptions. Previous observations have found that some jets are driven by base-field eruptions8–11, but only one such study, of only one jet, provisionally questioned the emerging-flux model12. Our observations support the view that solar filament eruptions are formed by a fundamental explosive magnetic process that occurs on a vast range of scales, from the biggest mass ejections and flare eruptions down to X-ray jets, and perhaps even down to smaller jets that may power coronal heating13,14. A similar scenario has previously been suggested, but was inferred from different observations and based on a different origin of the erupting minifilament15.

Solar X-ray jets are imaged by satellite-borne telescopes in space in the ~0.2–2.0 keV range. They are dynamic (with upward velocities of around 200 km s−1), long (about 5 × 104 km), narrow (8 × 103 km), and transient (with lifetimes of about 10 minutes)16,17. In the accepted version of the emerging-flux model of jet formation13,16–21, an emerging magnetic bipole enters a dominant-polarity (say, negative) ambient open magnetic field (that is, a field that extends far into the heliosphere), and the bipole’s minority-polarity (positive) side can reconnect with the coronal open field at the location of the magnetic-null region between the bipole and the ambient field. In this model, a burst of reconnection connects the outside of the bipole with the adjacent coronal field, producing a small loop on the outside of the emerging bipole’s minority-polarity foot, and reconnects the open field to the outside of the bipole’s majority-polarity foot. An X-ray jet develops as reconnection-heated material flows out along the new open-field strands. Moreover, in this model the presence of the X-ray jet bright point (JBP) at the edge of the jet’s base is explained by the existence of the small loop that is formed by reconnection at the emerging field’s edge. In an extension of the emerging-flux model, the emerged bipole explodes as it reconnects, forming a ‘blowout jet’ with a relatively broad spire13. (See Methods and Extended Data Fig. 1 for further details of the emerging-flux model.)

To assess observationally the production of X-ray jets, we analysed 20 jets (Extended Data Table 1) in the solar polar regions using X-ray images from the X-ray telescope (XRT) on the Hinode satellite22; this telescope detects a broad temperature range of coronal plasmas hotter than about 1.5 MK. We also used concurrent extreme ultraviolet (EUV) images from the Solar Dynamics Observatory’s (SDO’s) Atmospheric and Imaging Assembly (AIA)23, whose various filters detect plasmas primarily over narrow temperature ranges centred at, for example, approximately 0.05 MK, 0.6 MK, 1.6 MK or 2.0 MK, respectively, for wavelengths of 304 Å, 171 Å, 193 Å and 211 Å (see Methods).

Figure 1 shows a typical example of our results in both soft X-ray (Fig. 1a–c) and EUV (Fig. 1d–f) images. Between Fig. 1a and Fig. 1b, the jet’s spire, arched base, and JBP all begin brightening. Later (Fig. 1c), the spire extends higher, with the JBP positioned about 10º west of the spire. From a movie constructed from the XRT images (see Supplementary Video 1), we can see that the JBP starts to brighten at about 22:07 universal time (UT), with the spire becoming visible about 2.5 minutes later. Thus one could assume that the emergence of this jet fits with the emerging-flux model, whereby external reconnection (that is, reconnection occurring on the outside of the closed driving field24) of the emerging field forms the JBP and gives rise to the spire at a displaced location. However, observing the same feature in AIA 193 Å EUV images (Fig. 1 and Supplementary Video 1) does not support this interpretation. These images clearly show a dark feature, similar to a small-scale solar chromospheric filament (hereafter ‘minifilament’), moving upwards and laterally, starting at around 22:06 UT. Its velocity is ~40 km s−1 between 22:07 UT and about 22:10 UT, when it reaches the apex of the illuminated arched base of the X-ray jet. After 22:10 UT, the minifilament is expelled in the spire of an EUV jet that is the counterpart to the XRT jet. In the EUV images, the jet has both emission and absorption components, with the minifilament evolving into part of the jet. Notably, however, in both soft X-ray and EUV images, the JBP is at the location from which the minifilament erupted. Thus the JBP is the analogue of the commonly observed solar flare arcade that forms in the wake of larger-scale filament eruptions; such flare arcades are made by internal reconnection (that is, reconnection occurring on the inside of the closed driving field24) of the legs of the erupting closed field of a filament. This is not consistent with the JBP resulting from external reconnection, as proposed in the emerging-flux model.

We found an erupting minifilament to be discernible in AIA images of all 20 of the jets, with the minifilament’s eruption starting near the location of the JBP. In most cases, we could see that the JBP occurred where the minifilament (or part of the minifilament) had been rooted in the surface before ejection; we could not verify this arrangement in a few cases, in which the minifilament and JBP were along the same line of sight, but even then the observations are consistent with the JBP occurring at the location from which the minifilament was ejected. Typically, first the minifilament starts to lift off from the surface, and then the JBP starts to brighten. This is similar to the situation with large-scale filament eruptions, where the start of the eruption precedes the flare-brightening onset25. Apart from their size, the eruptions of minifilaments in the production of X-ray jets are indistinguishable from the commonly observed eruptions of larger filaments in the onsets of solar flares. In some cases (see Extended Data Table 1, event 4, event 9 and event 13, and possibly event 1), rather than the entire minifilament lifting off, there is a whipping-like motion, with the 1NASA/ Marshall Space Flight Center, Huntsville, Alabama 35812, USA. 2Center for Space Plasma and Aeronomic Research, University of Alabama in Huntsville, Huntsville, Alabama 35899, USA.

10.1038/nature14556

©2015 Macmillan Publishers Limited. All rights reserved
JBPs (flare) occurring below the whipping minifilament or at the location where the fastest moving part of the minifilament first detaches from the solar surface. Thus all cases are consistent with the JBP being a small flare arcade forming in the wake of the erupting minifilaments.2–4

We measured the lengths and velocities (as seen projected against the plane of the sky) of the minifilaments, during the period after they started to erupt but before they reached the jet-spire location. The average length of the minifilaments was $11''$ ($8 \times 10^4$ km) with a standard deviation of $4''$. This is much smaller than the sizes quoted for filaments from an extensive survey (3 $\times$ $10^4$ km to $1.1 \times 10^5$ km), justifying the use of the term ‘minifilaments’. (Perhaps identical minifilaments had been previously identified on the solar disk.) Our measured average minifilament length is equal to the average width of X-ray jets, consistent with the idea that the jet eruption is being driven by the minifilament eruption. We obtained mean velocities and a standard deviation for the erupting minifilaments of $31 \pm 15$ km s$^{-1}$. In all cases, the true sizes and speeds should tend to be larger than those plane-of-sky values.

X-ray jets have been classified as ‘standard’ or ‘blowout’ on the basis of the morphology of the spire and the intensity of the rest of the jet. Initially (Fig. 2a), two bipoles exist side by side, the larger one corresponding to what we usually observe as the base of the jet (compare with Fig. 1). The smaller bipole contains substantial free energy in the form of sheared and twisted magnetic field; that field holds a minifilament. As with the case of large-scale solar eruptions, this field becomes unstable by some process; it then erupts outwards, guided between the large bipole and the ambient open field. After the minifilament’s lift-off, internal reconnection occurs among the distended legs inside the minifilament field (Fig. 1b), making a ‘flare-arcade’ JBP. The spire starts to form as soon as the outer envelope of the minifilament-carrying erupting field begins external reconnection with the open field on the far side of the large bipole. External reconnection continues and soon reconnects the field threading the erupting minifilament with the far-side open field, injecting minifilament plasma along that open field. The external reconnection also adds a new hot layer to the larger bipole (larger red loop in Fig. 2c).

If the erupting minifilament-carrying field blows out beyond the large bipole’s apex (Fig. 2b, c), then widespread external reconnection results; this creates a broad jet spire characteristic of blowout jets. If the erupting field stalls near the apex of the large bipole (and/or if the eruption is weak enough), the external reconnection produces only a

Figure 1 | Erupting-jet example. An example jet from 17 September 2010, as detected in soft X-ray (Hinode/XRT, TiPoly filter; a–c) and EUV (SDO/AIA 193 Å; d–f). In b, the jet bright point (JBP) is visible as a localized brightening; in c, the jet is fully developed and offset eastward of the JBP.
narrow jet, characteristic of a standard jet. Examples of blowout jets are shown in Fig. 1, and in Extended Data Figs 2 and 3 and their corresponding videos (Supplementary Videos 2 and 3). Examples of standard jets are shown in Extended Data Figs 4 and 5 and their corresponding videos (Supplementary Videos 4 and 5).

The emerging-flux model fails to explain our observation of a JBP occurring below the erupting minifilament, which the scenario shown in Fig. 2 naturally explains. Also, an expectation of the emerging-flux model is that, as the external reconnection progresses, reconnected open field will occur progressively closer to the JBP than does open field that reconnected earlier\(^ {19}\). That is, the jet spire should drift towards the JBP in the emerging-flux model. Observations show, however, that more often than not the spire drifts away from the JBP\(^ {20}\). The schematic shown in Fig. 2 again explains this tendency for spire drift away from the JBP: the external reconnection of the erupting minifilament—carrying field produces reconnected open-field lines that in the corona stand progressively further away from the eruption’s source location, which is the location of the internal-reconnection flare arcade that is the JBP.

We have not addressed what leads to the minifilament eruptions we have detected. Some recent studies of on-disk coronal jets found that the miniature filaments probably resulted from the cancellation of magnetic flux in the hours leading up to the eruption\(^ {9,12,29,30}\). We suspect however that, as with large-scale eruptions, various agents could trigger the eruption, including flux cancellation and flux emergence. In the latter case, the flux emergence would trigger the minifilament’s eruption, rather than directly driving the jet as proposed in the emerging-flux model.

The minority-polarity flux in the base of an X-ray jet presumably arises from flux emergence of compact field loops into the dominant-polarity ambient field. It would therefore seem that many X-ray jets should be produced by these closed-field emergences, in the manner of the long-accepted emerging-flux model. However, that we found no X-ray jets formed in this way (at least for jets in polar coronal holes) suggests that external reconnection of the emerging closed field with the ambient open field occurs continuously and fast enough to keep an appreciable current sheet from building up at the magnetic-null region between the two fields, and that a burst of enough external reconnection to make an X-ray jet can be made only dynamically, driven by sudden eruption of the closed field as in a filament eruption. That is, the observed lack of X-ray jets formed in accordance with the emerging-flux model suggests that no current sheet of the scale of the overall system of two reconnecting fields can be formed gradually ( quasi-stably) in the low-beta magnetized plasma of X-ray jets (where ‘low-beta’ refers to a ratio of gas-to-magnetic pressures of much less than one), and by analogy not in similar reconnection events in other low-beta astrophysical settings either.

Figure 2 | Revised jet-eruption picture. Representation of the minifilament-eruption process that drives the formation of solar X-ray jets, as inferred from our observations. Black lines represent magnetic field, with arrows indicating polarities; red curves are newly reconnected field lines; blue features are minifilament material; yellow curve is the solar limb (the apparent edge of the Sun). From the initial state (a), the jet forms as the minifilament erupts (b, c), with reconnection locations indicated by red crosses (b, c). The JBP (bold red arc) forms at the location of filament lift-off (b, c). See Methods for more details.

Online Content Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

Received 28 August 2014; accepted 7 May 2015.

Published online 6 July 2015.

1. Shibata, K. et al. Observations of x-ray jets with the Yohkoh soft x-ray telescope. Publ. Astron. Soc. Jpn. 44, 173L–179L (1992).
2. Curtain, J. W. et al. Evidence for Alfvén waves in solar jets. Science 318, 1580–1582 (2007).
3. Yokoyama, T. & Shibata, K. Magnetic reconnection as the origin of x-ray jets and H\(_\alpha\) surges on the sun. Nature 375, 42–44 (1995).
4. Hirayama, T. Theoretical model of flares and prominences. Sol. Phys. 34, 323–338 (1974).
5. Shibata, K. et al. Hot-plasma ejections associated with compact-loop solar flares. Astrophys. J. 451, L83–L85 (1995).
6. Moore, R. L., Sterling, A. C., Hudson, H. S. & Lemen, J.R. Onset of the magnetic explosion in solar flares and coronal mass ejections. Astrophys. J. 552, 833–848 (2001).
7. Chen, P. F. Coronal mass ejections: models and their observational basis. Living Rev. Sol. Phys. 8, 1–92 (2011).
8. Moore, R. L., Tang, F., Bohlin, J. D. & Golub, L. H-alpha macrospicules—identification with EUV macrospicules and with flares in x-ray bright points. Astrophys. J. 218, 286–290 (1977).
9. Hong, J. et al. Coronal bright points associated with miniflare eruptions. Astrophys. J. 796, 73 (2014).
10. Raouafi, N.-E., Georgoulis, M. K., Rust, D. M. & Bernasconi, P. N. Micro-sigmoid as progenitors of coronal jets: is eruptive activity self-similarly multi-scaled? Astrophys. J. 718, 981–987 (2010).
11. Nisticò, G., Bothmer, V., Patelourakos, S. & Zimbardo, G. Characteristics of EUV coronal jets observed with STEREO/SECCHI. Sol. Phys. 259, 87–108 (2009).
12. Adams, M., Sterling, A. C., Moore, R. L. & Gary, G. A. Small-scale eruption leading to a blowout macrospicule jet in an on-disk coronal hole. Astrophys. J. 783, 11 (2014).
13. Moore, R. L., Sterling, A. C., Falconer, D. A. & Robe, D. The cool component and the dichotomy, lateral expansion, and axial rotation of solar x-ray jets. Astrophys. J. 769, 134 (2013).
14. De Pontieu, B. et al. The origins of hot plasma in the solar corona. Science 331, 55–58 (2011).
15. Shibata, K. Evidence of magnetic reconnection in solar flares and a unified model of flares. Astrophys. Space Sci. 264, 129–144 (1999).
16. Shimojo, M. et al. Statistical study of solar x-ray jets observed with the Yohkoh soft x-ray telescope. Publ. Astron. Soc. Jpn. 48, 123–136 (1996).
17. Savcheva, A. et al. A study of polar jet parameters based on Hinode XRT observations. Publ. Astron. Soc. Jpn. 59, S151–S178 (2007).
18. Nishizuka, N. Giant chromospheric anemone jet observed with Hinode and comparison with magnetohydrodynamic simulations: evidence of propagating Alfvén waves and magnetic reconnection. Astrophys. J. 683, L83–L86 (2008).
19. Moreno-Insertis, F. & Galgaard, K. Plasma jets and eruptions in solar coronal holes: a three-dimensional flux emergence experiment. Astrophys. J. 771, 20 (2013).
20. Archontis, V. & Hood, A. W. A numerical model of standard to blowout jets. Astrophys. J. 769, L21 (2013).
21. Fang, F., Fan, Y. & McIntosh, S. W. Rotating solar jets in simulations of flux emergence with thermal conduction. Astrophys. J. 789, L19 (2014).
22. Kosugi, T. et al. The Hinode (solar-B) mission: an overview. Sol. Phys. 243, 3–17 (2007).
23. Lemen, J. R. et al. The atmospheric imaging assembly (AIA) on the solar dynamics observatory (SDO). Sol. Phys. 275, 17–40 (2012).
24. Sterling, A. C. & Moore, R. L. Internal and external reconnection in a series of homologous solar flares. J. Geophys. Res. 106, 25227–25238 (2001).
25. Sterling, A. C. & Moore, R. L. Slow-rise and fast-rise phases of an erupting solar filament, and flare emission onset. Astrophys. J. 630, 1148–1159 (2005).
26. Bernasconi, P. N., Rust, D. D. M. & Hakim, D. Advanced automated solar filament detection and characterization code: description, performance, and results. Sol. Phys. 228, 97–117 (2005).
27. Wang, J. et al. Minifilament eruption on the quiet sun. I. Observations at Hs central line. Astrophys. J. 530, 1071–1084 (2000).
28. Savcheva, A., Cirtain, J. W., Deluca, E. E. & Golub, L. Does a polar coronal hole’s flux emergence follow a Hale-like law? Astrophys. J. 702, L32–L36 (2009).
29. Shen, Y., Liu, Y., Su, J. & Deng, Y. On a coronal blowout jet: the first observation of a simultaneously produced bubble-like CME and a jet-like CME in a solar event. Astrophys. J. 745, 164 (2012).
30. Young, P. R. & Muglach, K. A. Solar dynamics observatory and Hinode observations of a blowout jet in a coronal hole. Sol. Phys. 298, 3313–3329 (2014).

Supplementary Information is available in the online version of the paper.

Acknowledgements A.C.S. and R.L.M. were supported by funding from the Heliophysics Division of NASA’s Science Mission Directorate through the Living With A Star Targeted Research and Technology Program (LWS TR&T), and the Hinode Project. Both benefited from TR&T discussions and from discussions with S. K. Antiochos. We thank D. M. Zarro for assistance with video development. A.C.S. benefited from discussions held at the International Space Science Institute (ISSI; Switzerland) International Team on Solar Coronal Jets (led by N. Raouafi). Hinode is a Japanese mission developed and launched by the Institute of Space and Astronautical Science (ISAS) of the Japan Aerospace Exploration Agency (JAXA), with the National Astronomical Observatory Japan (NAOJ) as a domestic partner, and NASA and the Science and Technology Facilities Council (UK) as international partners. It is operated by these agencies in cooperation with the European Space Agency and Norwegian Space Agency.

Author Contributions A.C.S. carried out the reduction, analysis, and interpretation of XRT and AIA data, software development, and manuscript preparation. R.L.M. interpreted the results and reviewed the manuscript. D.A.F. developed software, and assimilated and calibrated AIA data. M.A. discovered and analysed the seminal jet event that motivated this broader investigation, and carried out manuscript formatting and review.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to A.C.S. (alphonse.sterling@nasa.gov) or R.L.M. (ron.moore@nasa.gov).
Emerging-flux model. According to the emerging-flux model\textsuperscript{20–22} (Extended Data Fig. 1), for the formation of solar coronal jets, an emerging bipolar enters a dominant-polarity (negative in Extended Data Fig. 1) ambient open field, and the bipolar’s minority-polarity (positive side) can reconnect with coronal field at the location of the magnetic-null region between the bipolar and the ambient field. After enough of the bipolar has emerged, a burst of reconnection joins the outside of the bipolar with the nearby coronal field (Extended Data Fig. 1b), resulting in two reconnection products: a small loop on the outside of the base of the emerging bipolar’s minority-polarity side, and an open field connecting the bipolar’s majority-polarity side with the open coronal field, giving a new footpoint connection for that coronal field. This type of reconnection has been called ‘interchange’\textsuperscript{31}, or ‘external’\textsuperscript{24}, because the reconnection is on the outside of the closed driving field (the emerging field in this case). An X-ray jet develops as reconnection-heated material flows out along the new open-field strands. Additionally, the external-reconnection-formed small loop at the emerging field’s edge is the model’s explanation for the JBP (also called a ‘hot loop’)\textsuperscript{1} observed at the edge of the jet’s base. According to the previous view of blowout jets\textsuperscript{32}, the idea was that the external reconnection causes and/or is driven by ejective eruption (blowout) of the emerging bipolar, which is assumed to contain substantial nonpotential (that is, twisted) magnetic field, driving that bipolar’s eruption along the ambient open field to make a broad jet spire\textsuperscript{33}.

Instrumentation and data. For our X-ray images, we use data from the Hinode/XRT with 30-s cadence and 1° pixels. XRT detects a broad range of temperatures, but has highest sensitivity for temperatures of greater than about 1.5 MK, even with the TiPoly filter used for the observations presented here. (Among XRT’s filters, the TiPoly filter detects relatively cool X-ray-emitting plasmas.) For each jet in Extended Data Table 1, we studied concurrent EUV images from SDO/AIA, which has 0.6° pixels and 12-s cadence. Our final movies and figures were formed by summing the frames in pairs, and therefore the resulting movies were generally of 1-min cadence and 24-s cadence respectively for XRT and AIA. This summing blurs the images somewhat, but renders subtle features, such as X-ray jets and some of the fainter EUV-detected minifilaments, much easier to discern. For many of the X-ray jets of our study, we examined all of the AIA EUV channels, which are tuned to wavelengths of 304 Å, 171 Å, 193 Å, 211 Å, 131 Å, 335 Å, and 94 Å; these have strong responses to logarithmic temperatures (in Kelvin) of about 4.7, 5.8, 6.2, 6.3, 7.0, 6.4, and 6.8 respectively (although some channels are multivalued\textsuperscript{23}). Usually there was little new information in the hotter 131-Å, 335-Å, and 94-Å channels, and so we did not inspect these hotter channels for some of the jets. We applied standard processing routines from the Solarsoft software library\textsuperscript{25} to the XRT and AIA images.

In total we examined 20 X-ray jets, initially selected during an earlier study\textsuperscript{34}, in which the JBP was obvious in the X-ray images (Extended Data Table 1). Each event of Extended Data Table 1 is categorized as ‘standard’, ‘blowout’, or ‘ambiguous’ based on its morphology in the XRT images (and, in some cases, in the AIA 131-Å images also). Blowout jets are those in which the entire bipolar, brightened and the spire broadened to span approximately the width of the base; standard jets are those in which only the JBP brightened substantially in the base and the spire remained narrow compared with the span of the base. (The JBP is also referred to as the ‘hot loop’\textsuperscript{1}, ‘bright loop’\textsuperscript{3}, ‘bright point’\textsuperscript{11,13,33}, and ‘bright footpoint’\textsuperscript{33}.)

In each blowout jet in Extended Data Table 1, the minifilament eruption seemed to be ejective; the erupting closed field apparently blows out into the ambient open field. In this case, much or all of the filament material escapes from the closed field onto the open field. In the events of Extended Data Table 1 that are categorized as standard jets, a minifilament eruption was detectable, but usually that eruption either did not seem to be ejective, or was perhaps ejective but weak or faint. In event 4, a mini-filament (best seen at 304 Å) has a whipping motion from the location that the JBP was obvious in the X-ray images (Extended Data Table 1). Each standard jet shows an ejective minifilament, similar to the jets identified as blowout jets, but it does not make a broad spire. In that case it appears that the minifilament erupted far enough for much of it to escape into the open field through external reconnection, but not enough to blow out violently and form a broad jet. In comparison with the blowout jets, more of the filament material remains trapped within the closed field.

Our other standard jets (events 5 and 19), and the ambiguous jet (event 11), may also be partially confined and partially ejective minifilament eruptions. In these cases, some of the minifilament material escapes onto the open field, and some of it remains in the closed field. In this sense, we envisage a continuum of jet manifestations, between pure blowout jet (where the filament field would push far into the opposite-polarity open field, making a broad jet, and all of the filament material would eventually escape onto that open field), and a pure standard jet (where only the envelope of the closed field reconnects with the opposite-polarity open field, and none of the closed field containing the cool filament material undergoes external reconnection). Our view of standard jets as being due to confined minifilament eruptions, partially confined minifilament eruptions, and/or weak ejective minifilament eruptions is still speculative. Further study will be required to understand fully the various morphological differences among jets.

Minifilament measurement details. We measured the lengths and velocities (projected in the plane of the sky normal to the Earth–Sun line-of-sight) of the minifilaments during the period after they started to erupt but before they formed a jet or reached the apex of the base (below the jet spire). We usually used the 171-Å, 193-Å or 211-Å AIA channels for these measurements; only for events 4, 7 and 10 did we find the 304-Å channel preferable for determining minifilament properties in our data set. We obtained mean velocities for the erupting minifilaments of 31 ± 15 km s\textsuperscript{-1}; if the velocities are weighted inversely with their uncertainty (Extended Data Table 1), the weighted mean velocity and weighted standard deviation are 24 km s\textsuperscript{-1} and 13 km s\textsuperscript{-1}, respectively.

The jet-formation process in our picture. As shown in Fig. 2, we envisage that initially a minifilament-carrying, nonpotential, relatively compact core of magnetic field (or magnetic arcade) exists next to (and shares the minority-polarity flux with) a relatively large bipole (Fig. 2a). An unspecified process destabilizes the smaller bipole so that it erupts, with the minifilament being channelled between the large bipole and the overlying open field. Upon reaching the open coronal field on the far side of the large bipole, the field carrying the minifilament reconnects with that field (Fig. 2b), and a jet, often including substantial minifilament material, is ejected along the newly reconnected open field (Fig. 2c). This reconnection also adds field lines to the large bipole. Internal reconnection (the lower red cross) of the minifilament-carrying field also occurs (Fig. 2b); this reconnection is inside the erupting lobe of the double bipole, and forms a flare arcade (the JBP) in the wake of the ejected minifilament.

This process of X-ray-jet formation is analogous to the formation of commonly observed flare arcades in typical large-scale solar eruptions; that is, the erupting lobe of the system erupts as in a ‘typical’ large-scale eruption, as pictured in, for example, figure 1 of ref. 5 or figure 1 of ref. 6. In our jet-formation picture, this process is occurring on a smaller scale, so that the filament of those typical models corresponds to our minifilaments. However, rather than a filament travelling directly outwards as in those large-scale eruptions, in the case of X-ray jets the minifilament travels along the curved path between the adjacent bipole and distorted ambient coronal field. (The coronal field is distorted by the magnetic field of the two biopoles.) As long as the erupting minifilament is on the near side (that is, the side of its origin) of the apex of the neighbouring bipole, no reconnection occurs between the erupting-bipole-field enveloping the filament and the ambient coronal field; this is the three-dimensional case (as in the two-dimensional schematic, but we still expect the basic picture to hold.) We will consider what happens when the enveloping field reaches the far side of the apex shortly. First, however, looking again at the schematics of the typical large-scale eruptions\textsuperscript{24}, it can be seen that the field lines beneath the erupting filament reconnect (this is what we are calling internal reconnection) to form hot flare loops near the solar surface. In our analogous schematic (Fig. 2), these flare loops correspond to the JBP. While the small lobe of the double bipole in Fig. 2 is erupting in this fashion, the neighbouring bipole remains largely inert, except for the addition of the new field via external reconnection, as mentioned above. If we now consider what happens when the erupting minifilament reaches the far side of the apex of the neighbouring bipole (Fig. 2b). Because the field orientations are then opposite, the erupting field enveloping the minifilament and the far-side ambient coronal field can undergo reconnection; because this reconnection is between the field of the erupting bipole and the coronal field that is external to that erupting bipole, we call this external reconnection. This external reconnection adds heat to the reconnected field lines, making a hot jet spire along the open field lines and forming hot loops over the adjacent bipole (red curves in Fig. 2c). This external reconnection progressively erodes the field enveloping the cool minifilament material. If this erosion of the enveloping field stops before the filament has lost all of its cool material, for example, the erupting minifilament-carrying bipole does not have enough energy to travel deep into the far-side ambient-field region—then the cool material never reaches the open field (and the spire receives no cool material). Rather, the filament plasma remains trapped in the closed field in the base of the jet. This may be how the
standard jets are formed; only a narrow hot spire forms if the erupting minifilament-carrying bipole does not go far into the ambient-field region.

In a blowout jet, the eruption continues deeper into the ambient field region of oppositely directed polarity to make a broader spire than is depicted in Fig. 2c. The envelope around the cool-minifilament material is completely eroded away, and so the cool material escapes onto the open ambient coronal field, forming a cool jet. In this sense, the eruption of the minifilament is analogous to ejective eruptions of typical large-scale cases. (Some standard jets appear to be weak versions of such ejective jets.) The drawings in Fig. 2 are tailored to depict the jet in Fig. 1 (Jet 18 in Extended Data Table 1), which is a blowout jet.

The external reconnection of the erupting-minifilament field with the open field also adds a new hot layer to the larger bipole (larger red loop in Fig. 2c); this reconnection product from earlier eruption episodes might have created the ‘initial’ large bipole (large black loops of Fig. 2a). Other possibilities for the initial large bipole are that it and the filament-carrying bipole are two asymmetric lobes of a so-called anemone field region\(^6\). That anemone region could be due to recently emerged magnetic flux, or it could have formed over time via surface-flux migration and cancellation\(^6\).

A schematic for X-ray jets similar to that of our Fig. 2 is shown in figure 8b of ref. 15. That figure was derived from data from earlier satellite missions, before the high-resolution, high-cadence, multiple-EUV-wavelength data of SDO/AIA. There is, however, a difference between the picture of ref. 15 and our picture.

The proposal there is that a plasmoid (which might correspond to our minifilament) erupts from the external-reconnection site of the emerging-flux model (Extended Data Fig. 1), the pre-eruption plasmoid being in the current sheet between the emerging flux and the ambient coronal field. (Also, figure 6 of ref. 15 explicitly depicts an emerging-flux origin for X-ray jets.) In contrast, our proposal is that X-ray jets, at least in coronal holes, are a miniature version of large-scale flares and coronal mass eruptions, regardless of whether there is emerging magnetic flux. In our view, before eruption the minifilament resides in sheared field (or in a twisted-field magnetic flux rope) in the core of a magnetic arcade, instead of in a current sheet. More generally, in our view the triggering and eruption of the minifilament may include any of a multitude of processes and subprocesses proposed for large-scale eruptions, including those listed in the main text, and others\(^7\). Determining whether the pre-eruption minifilaments that erupt in jets are located at an external-reconnection current sheet (as suggested in ref. 15), or instead reside in a magnetic arcade, as we envisage, requires further observational study.

In our AIA movies the developing jets show clear rotation in some cases, such as the jet of Fig. 1 (Supplementary Video 1). Other jets, however, show only partial rotation (for example, Extended Data Fig. 2 and Supplementary Video 2), or no obvious rotation (for example, Extended Data Fig. 3 and Supplementary Video 3). Because we have not identified a clear pattern regarding the rotations and the resulting jets, we do not address this topic further here.

**Cause of minifilament-eruption onset.** Given that we have not examined jets that originate at low solar latitudes, we cannot adequately see the causes (triggering) of these magnetic eruptions. As with large-scale filament eruptions, several triggering agents could be responsible, including flux cancellation or even flux emergence. Our main point here is that, independently of the cause of the minifilament-eruption onset, the jets all result from those minifilament eruptions, with the JBP being the ‘flare’ that occurs in conjunction with those minifilament eruptions.

As stated in the main text, however, several other studies\(^8\) found on-disk coronal jets to occur in conjunction with magnetic flux cancellation. One study\(^9\) searched for emerging flux beneath a jet, but found no noticeable signature of emergence. A different study\(^10\) also searched for but did not find emerging flux below an on-disk coronal jet. Another study\(^11\) found mini coronal mass eruptions, perhaps resulting from ‘small filament eruptions’, that may be similar or identical to the jets we discuss here; that study reports the eruptions to occur at sites of ‘twisting small concentrations of opposite polarity magnetic field’, and again there was no detection of emerging flux. Similar jets have been reported elsewhere\(^12\), but without direct magnetic field observations.

We have found two studies of on-disk jets where emerging flux was reported. In the first\(^13\), though emergence occurred, a microflare and an EUV jet happened only after cancellation of flux in the region of the flux emergence. Similarly, in the second study\(^14\) flux emergence occurred, but two jets occurred at about the time that the emerged flux underwent cancellation with the neighbouring field. In that case\(^14\), the jet observations were from XRT, and were of jets occurring in on-disk coronal holes; so those observations are on-disk complementary examples of the near-limb XRT polar-coronal-hole jet observations that we present here.

On balance, then, the on-disk coronal jet studies suggest that flux cancellation is often crucial to jet onset. In light of our findings, we expect that, in those earlier observations, the cancellation probably resulted in minifilament eruptions that produced jets, with flares occurring in the wake of those eruptions and appearing as JBPs.
Extended Data Figure 1 | Emerging-flux model for the formation of solar X-ray jets. The commonly accepted mechanism for jet formation\(^1\). Black lines represent magnetic field, with arrows indicating polarity; the yellow curve is the solar limb; the thick red curve in a represents a plasma current sheet; the red cross in b shows the location of field reconnection. a, Initial state. b, Jet formation: flux emergence purportedly forces reconnection at the current sheet (red cross), resulting in new closed-loop field (red loop), and new connections to the open coronal field (thin red line), along which the X-ray jet (purple) flows. According to this model, the new reconnection loops appear as the JBP. Previous scenarios for ‘blowout jets’\(^{13,33,45}\) have been variations of this model.
Extended Data Figure 2 | Jet of 2010 September 9, 22 UT.  a–c, XRT, and d–f, 193-Å AIA images of the jet. Arrows show: b, the developing JBP; c, the X-ray-jet spire; and d, the minifilament. In e, both arrows point to segments of the minifilament, which split during eruption; in f, both arrows point to the edges of a broad jet. In d, the blue bar shows our estimate of the size of the minifilament, the value of which appears in Extended Data Table 1. See Supplementary Video 2 for animations. This is event 12 of Extended Data Table 1. North is to the top and west to the right of these images (and all other solar images in this paper).
Extended Data Figure 3 | Jet of 2010 September 9, 23 UT. a–c, XRT, and d–f, 211-Å AIA images of the jet. Arrows show: b, the developing JBP; c, the X-ray-jet spire; and d, the minifilament starting to erupt. The blue bar in d shows our estimate of the size of the minifilament. The AIA images show a smaller field of view than the XRT images. See Supplementary Video 3 for animations. This is event 13 of Extended Data Table 1.
Extended Data Figure 4 | Jet of 2010 August 28, 13 UT. a–c, XRT, and d–f, 304-Å AIA images of a ‘standard’ jet. Arrows show: b, the X-ray jet spire; c, the X-ray jet spire, showing drift since b; d, the minifilament starting to erupt; e, ‘rolling’ filament (see Methods). The blue bar in d shows our estimate of the size of the minifilament. The grey-scale images show the filament better than the colour images for this event. See Supplementary Video 4 for animations. This is event 7 of Extended Data Table 1.
Extended Data Figure 5 | Jet of 2010 August 28, 11 UT.  a–c, XRT, and d–f, 211-Å AIA images of a ‘standard’ jet. The dark spot northwest of centre in the XRT images is an artefact. Arrows show: b, the JBP; c, the X-ray jet spire; d, the minifilament moving upwards; e, the minifilament near the apex of the jet base, with the jet spire starting to develop. The AIA images show a smaller field of view than the XRT images. The blue bar in d shows our estimate of the size of the minifilament. See Supplementary Video 5 for animations. This is event 6 of Extended Data Table 1.
Extended Data Table 1 | The X-ray jets studied here

| Event | Date$^a$ | Start; End$^b$ | $x, y$ (arcsec)$^c$ | Type$^d$ | Fil. Size$^e$ (arcsec) | Fil. Speed$^e$ (km s$^{-1}$) |
|-------|----------|----------------|---------------------|---------|-----------------------|-----------------------------|
| 1     | 2010 Jul 24 | 15:56; >16:15 | -60, 950            | blowout | 17                    | 14 ± 2                      |
| 2     | 2010 Jul 25 | 12:29; 12:46  | 140, -950           | blowout | 10                    | 30 ± 10                     |
| 3     | 2010 Aug 26 | 14:13; >14:16 | 100, 950            | blowout | 10                    | 28 ± 5                      |
| 4     | 2010 Aug 27 | 11:35; 12:17  | 30, 920             | standard| 20                    | 50 ± 5$^f$                 |
| 5     | 2010 Aug 27 | 11:40; 12:20  | -50, 920            | standard| diffuse$^f$            | 28 ± 5$^f$                 |
| 6     | 2010 Aug 28 | 11:40; 12:03  | -130, 940           | standard| 5                     | 28 ± 5                      |
| 7     | 2010 Aug 28 | <13:41; >13:48| -70, 840            | standard| 17                    | rolling                    |
| 8     | 2010 Sep 05 | 21:14; 21:35  | 30, 840             | blowout | 10                    | 28 ± 5                      |
| 9     | 2010 Sep 08 | 01:29; 01:44  | 40, 935             | blowout | 6                     | 19 ± 5                      |
| 10    | 2010 Sep 09 | 20:14; 20:33  | 20, 770             | blowout | 17                    | 73 ± 8                      |
| 11    | 2010 Sep 09 | 20:21; 20:40  | 60, 850             | ambiguous| 12                   | uncertain$^g$               |
| 12    | 2010 Sep 09 | 22:05; 22:31  | 0, 910              | blowout | 7                     | 13 ± 3                      |
| 13    | 2010 Sep 09 | 23:52; 00:06  | -120, 950           | blowout | 9                     | 33 ± 5                      |
| 14    | 2010 Sep 10 | 00:01; 00:09  | -10, 880            | blowout | 7                     | 50 ± 10                     |
| 15    | 2010 Sep 11 | 00:39; 00:50  | 80, 950             | blowout | 8$^f$                 | 19 ± 5$^f$                 |
| 16    | 2010 Sep 11 | <01:08; 01:27 | -120, 950           | blowout | 13                    | 40 ± 8                      |
| 17    | 2010 Sep 17 | 20:39; 21:08  | -20, 840            | blowout | diffuse$^h$           | 33 ± 8$^h$                 |
| 18    | 2010 Sep 17 | 22:08; 22:18  | 30, 960             | blowout | 7                     | 40 ± 5                      |
| 19    | 2010 Sep 19 | 19:47; 20:23  | 20, 880             | standard| 10                    | 20 ± 5                      |
| 20    | 2010 Sep 27 | 00:39; 00:43  | 0, 960              | blowout | 10                    | 20 ± 5                      |

$^a$Date the event started. $^b$Time period (in UT) during which a clearly detectable jet and/or compact JBP is visible in XRT images. $^c$Indicate that the jet started before or continued after, respectively, the indicated times during gaps in XRT data. $^d$x, y location of the jet in AIA images in heliocentric coordinates. $^e$Morphological classification of the X-ray jet based on ref. 13. $^f$Line-of-sight projected size/speed of the minifilament near the time of eruption onset; size uncertainty less than about 3">$^g$Approximate size/speed of the minifilament diffuse or faint, or identification less certain than in other cases. $^h$Accurate speed measurement not possible owing to image shifts during eruption time. $^i$Minifilament too diffuse for size measurement, but moving structures can be tracked for velocity estimate.