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SOLAR POLAR X-RAY JETS AND MULTIPLE BRIGHT POINTS: EVIDENCE FOR SYMPATHETIC ACTIVITY

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ABSTRACT

We present an analysis of X-ray bright points (BPs) and X-ray jets observed by *Hinode*/X-Ray Telescope on 2007 November 2–4, within the solar northern polar coronal hole. After selecting small subregions that include several BPs, we followed their brightness evolution over a time interval of a few hours, when several jets were observed. We find that most of the jets occurred in close temporal association with brightness maxima in multiple BPs: more precisely, most jets are closely correlated with the brightening of at least two BPs. We suggest that the jets result from magnetic connectivity changes that also induce the BP variability. We surmise that the jets and implied magnetic connectivity we describe are small-scale versions of the active-region-scale phenomenon, whereby flares and eruptions are triggered by interacting bipoles.

Key words: Sun: activity – Sun: corona

Online-only material: animations

1. INTRODUCTION

X-ray jets were first reported by Shibata et al. (1992) based on observations from the Soft X-Ray Telescope (SXT) on *Yohkoh*. They found most jets to occur in conjunction with X-ray-emitting microflares, and Shimojo et al. (1996) confirmed this association with a statistical study. Yokoyama & Shibata (1995) and subsequent studies have shown with numerical simulations that X-ray jets can occur together with microflares, via magnetic reconnection between an emerging bipole and a pre-existing "open" magnetic field. Most of the jets detected with SXT were outside of solar coronal holes (CHs).

The *Hinode*/X-Ray Telescope (XRT) experiment (Golub et al. 2007) has been crucial in revealing the occurrence of hot, high-speed, collimated jets in polar CHs, in far larger numbers than expected on the basis of previous observations (Cirtain et al. 2007). *Yohkoh* saw fewer jets in CHs, likely due in part to the poorer time cadence compared to XRT, and possibly also due in part to the ability for XRT to detect cooler temperature plasmas than SXT (Narukage et al. 2011). Interest in these ejective events is twofold: (1) their high number suggests they may have a role in coronal heating/solar wind acceleration, and (2) both observational and modeling efforts aim at understanding whether these phenomena are analogous to large-scale coronal mass ejections (CMEs), surges, and flares. Indeed, Moore et al. (2010) identified two kinds of X-ray jets fueled by reconnection, "standard jets" and "blowout jets," the latter representing miniature versions of the large-scale eruptions that give rise to CMEs (standard jets lack such an eruption). As in the SXT-observed jets, standard jets are the consequence of flux emergence within the unipolar field of the CH—originating at the time a bright point (BP) is being born (and possibly leaving no BP after their decay)—and have been successfully modeled by different authors (e.g., Moreno-Insertis 2008).

CHs host other small-scale features: hereafter, we focus on BPs, identified in the late 1960s (Vaiana et al. 1970) as roundish features, with a diameter ≈10″–20″, that overlie small-scale bipolar magnetic regions, have a lifetime of hours/day, and temperatures on the order of (1–2) × 10^6 K (e.g., Golub et al. 1974, 1977). It has been found that BPs are at least in some cases associated with CH jets (e.g., Doschek et al. 2010), similar to microflares and the SXT jets. Filippov et al. (2009) analyzed the formation of jets above small bright formations in polar CHs, suggesting a further type of X-ray jet not initiated by reconnection. BPs show intensity fluctuations on timescales of a few minutes to hours (e.g., Kariyappa & Varghese 2008). Previous works have dealt with different aspects of individual events. The present paper, on the contrary, focuses on the interaction between closely located CH BPs that appear to undergo intensity fluctuations as a group: in other words, complexes of BPs undergo coordinated intensity variations; sometimes these fluctuations accompany jet occurrence.

In this Letter, we investigate the question of whether the BP complex intensity changes are *correlated* with jet occurrence, and consider implications for such a correlation for the jet-production mechanism. We examined *Hinode*/XRT observations of BP complexes and made a photometric analysis of their brightness fluctuations over several hours. We then searched through the data for jets occurring within the BP complex. Based on our findings, we present a new aspect of X-ray jets that is perhaps critical to their generation.

2. OBSERVATIONS

We analyzed *Hinode*/XRT observations of the northern polar CH, acquired on 2007 November 2–4. The XRT images have a cadence of 1 minute, a spatial resolution of 1.032 arcsec pixel^{-1}, and have been calibrated with the standard tools, including the Solar SoftWare packages's xrt_prep.pro IDL routine. We selected two sub-regions of the CH where several BPs are present, as shown in Figure 1. Individual BPs within the sub-regions of Figure 1 were marked off by rectangular boxes, and we follow these boxes (tracking solar rotation) over the entire period of our study. For each BP we analyzed, we verified that

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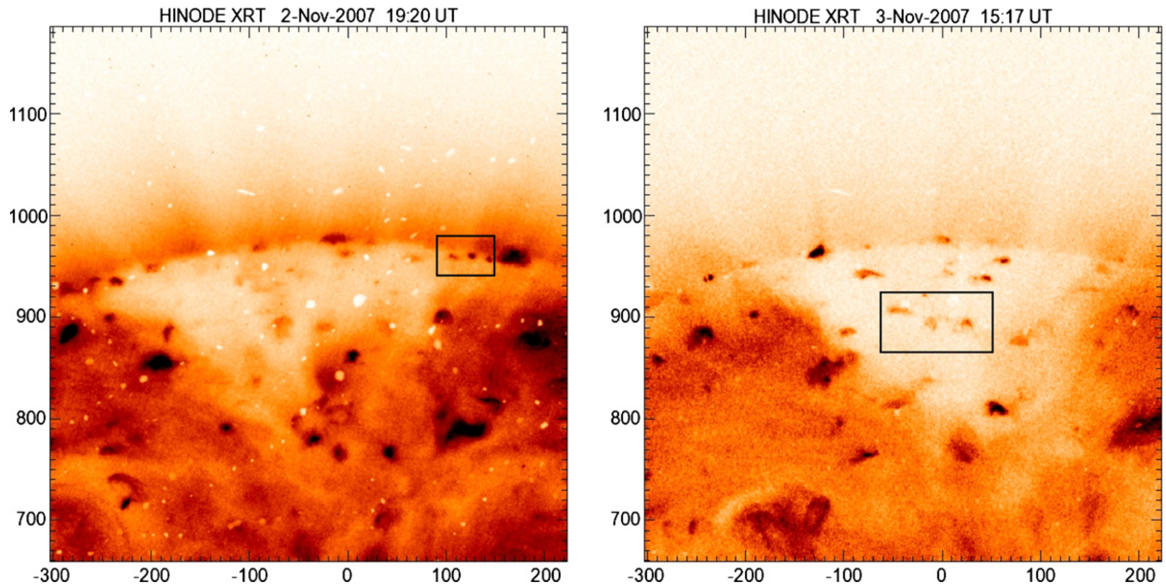

Figure 1. *Hinode*/X-Ray Telescope images of the north polar coronal hole, with superposed small rectangular areas selected for: our first study, over 2007 November 2–3 (left panel); and our second study, over 2007 November 3–4 (right panel). The x- and y-axes are arcseconds from Sun center. Left panel: Al-mesh image taken on November 2; right panel: Al-poly image taken on November 3. North is upward and west to the right in these and all solar images in this Letter.

(Animations of this figure are available in the online journal.)

the box we defined contained within its boundaries the entirety of the BP, for the duration of that BP's lifetime.

Brightness fluctuations of the BPs have been evaluated by summing the intensities of all pixels within the boxes and subtracting a background value. The latter has been estimated by summing the intensity values of all pixels along the borders of the boxes and normalizing the value we obtained to give the average background value per pixel. The following subsections describe the sequence of events observed in the first data set (acquired on November 2/3) and in the second data set (acquired on November 3/4) within the selected sub-regions.

2.1. First Data Set: Bright Points and Jets on 2007 November 2/3

Within the sub-region shown in the left panel of Figure 1, we identified seven BPs over ≈20 hr of observations, from November 2, 11:45 UT to November 3, 08:00 UT. During this period, some BPs fade out, while others become visible.

Figure 2 shows the variation in intensity (DN/s) with time of all seven BPs. Solid lines are color coded, each corresponding to a specific BP. In order to clearly correlate jet events with a BP activity increase, we define "local brightness maxima" as brightness intervals whose values are at least 6σ higher than the 1 hr averaged background brightness curve. Such maxima are highlighted in the figure with thicker lines, and have a typical full width at half-maximum of about 15 minutes. Jets observed within the examined sub-region are represented, along the abscissa, by small boxes sequentially numbered, whose color matches the color of the BP where the jet originates. The width of these jet boxes gives the duration of the respective jet, and their hues are roughly proportional to the respective jet's brightness. The time resolution adopted for the plot is that of the data (about 80 images per hour), but a four-point running mean of the original data is used in the figure. Weaker jets have been identified only after summing up a few images, and thus they have a degraded temporal resolution compared to the original data. Whenever the duration of two events (either BP local brightness maxima or jets) at least partially overlap, they are considered to be "almost simultaneous."

From the top panel of Figure 2, we find the following when a jet occurs. (1) The BP at the jet's base most of the time brightens almost simultaneously with the jet; seven out of nine jets do this, with the exception of J7, which does not show any significant BP brightness increase, and J5, which has a delayed (15 minute) BP brightness maxima. (2) Almost always, there is also a brightening in a nearby BP, where "nearby" means within the rectangular box under study; seven out of nine cases are like this, with the exceptions being J3 and J5. These points suggest that jets are the manifestation of some kind of activity that involves multiple BPs, rather than a lone BP. In addition, we have found that even in cases where jets appear to be accompanied by fluctuations in a single BP only, they might be correlated with one or more additional BPs located just outside the studied region. For example, the jet J5 is related with a huge brightness increase of a BP centered at west 165″, north 960″, hereafter BP10 (see Figure 1, left panel), whose brightness versus time profile appears in Figure 3.

So in addition to the above two conclusions, we may add a third: (3) caution should be exerted whenever jets appear not to be accompanied by multiple BP brightness fluctuations, because they may be associated with peaks of BPs external to the examined area. We conclude that seven out of nine jets observed in this first data set are associated with at least two BP maxima, three of them being correlated with peaks in three BPs (J1, J8, and J9).

In most cases there is an apparent propagation of energy/disturbances through the BPs complex. In Figure 4 (upper panels), we present a typical example of a propagating brightness fluctuations accompanied by jet occurrence. The peak brightness of BP3a (at ≈12:40 UT) is followed (after ≈6 minutes) by the peak brightness of BP3b, which, in turn (after ≈4 minutes), is followed by the simultaneous brightenings of BP1 and BP5a, and, 6 minutes later, by the BP5b maximum. Along with this sequence of brightenings, two jets occur: a brief jet (Ja) is observed at the time of the BP3 maximum, and

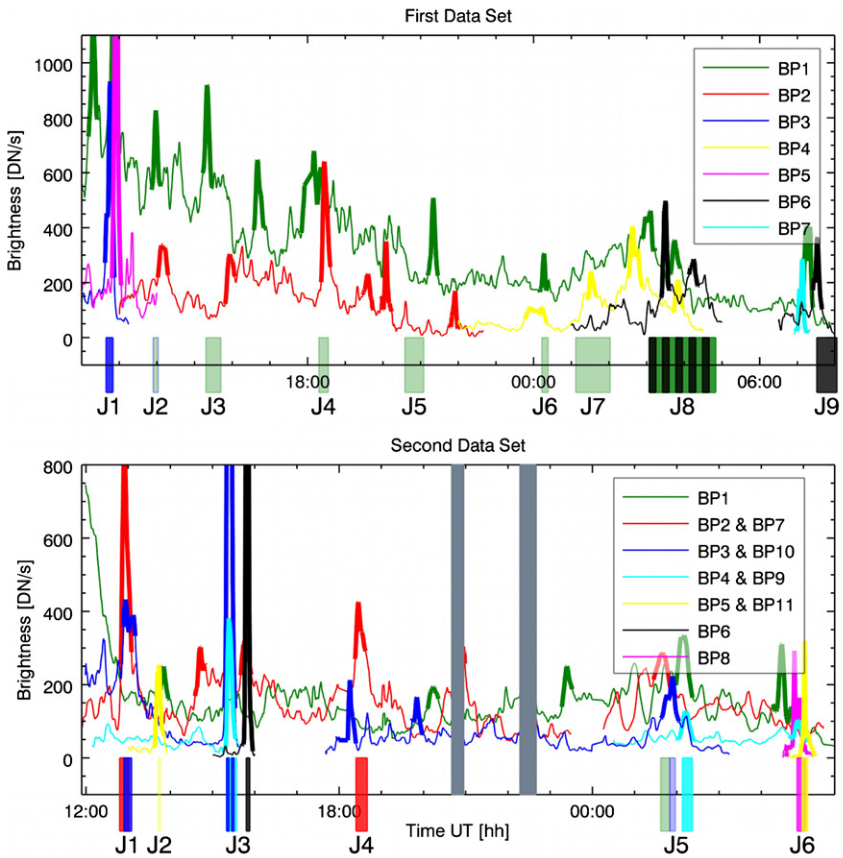

Figure 2. Top: bright point (BP) brightness (DN/s) profiles as functions of time, within the coronal hole (CH) region selected on 2007 November 2. Different BPs are identified by different colors, with intensities determined as explained in the text. Thicker lines highlight the "local brightness maxima." Boxes along the abscissa indicate jets, with the colors the same as that of the BP where the respective jets originate, the box width giving the duration of the jets, and the box hue giving an approximate relative indication of the jet intensity. The horizontal axis gives time (hours), starting on 2007 November 2, 12:00 UT; the full data set covers ≈20 hr. We point out that the two colored box J8 corresponds to a unique jet originating in BP1 and gradually shifting to BP6. Bottom: same as the top plot, but for the CH region selected on 2007 November 3. Time (hours), along the horizontal axis, starts on 2007 November 3, 12:00 UT; the full data set covers ≈18 hr. Between 13 and 16 UT, some local brightness maxima are so intense that they fall off the vertical scale of the plot. The gray shaded vertical stripes around 21 and 22 UT correspond to time intervals of noisy data that we omitted from our analysis.

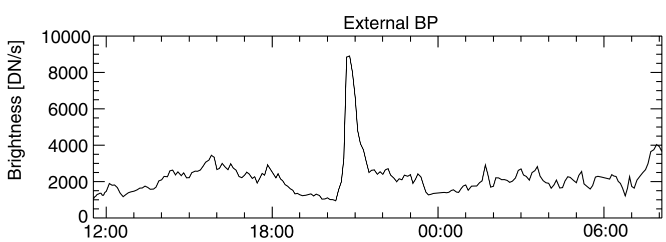

Figure 3. Brightness vs. time profile of BP10, a bright point located just outside the studied region. The time (hours), given by the horizontal axis, starts on 2007 November 2, 11:45 UT.

a second one (Jb), lasting about 3 minutes, occurs at the time when BP3b reaches its brightness maximum. This sequence of events is summarized in Table 1 (top section), where jets and BPs appear with the same notation used in the upper panels of Figure 4.

2.2. *Second Data Set: Bright Points and Jets on 2007 November 3/4*

Figure 2 (bottom panel) shows the BP brightness fluctuations and jets occurring in the CH sub-region selected on 2007 November 3/4 (right panel of Figure 1). This plot is based on data taken in the Al_poly filter. The Al_mesh filter used in the previous data set is more sensitive to cooler temperatures than is the Al_poly. Nonetheless, we find similar results in both data sets regarding the correlation between BP intensity fluctuations and

Table 1
Time Sequences for Two Multiple Brightenings Events

Date	Time	Event
First Data Set		
Nov 2	12:40	Maximum for BP3a
Nov 2	12:40	Start and end of Ja
Nov 2	12:44	Start of Jb
Nov 2	12:46	Maximum for BP3b
Nov 2	12:47	End of Jb
Nov 2	12:50	Maximum for BP1
Nov 2	12:50	Maximum for BP5a
Nov 2	12:56	Maximum for BP5b
Second Data Set		
Nov 4	01:41	Start of Ja from BP1
Nov 4	01:52	End of Ja
Nov 4	01:53	Start and end of Jb
Nov 4	01:53	Maximum for BP10
Nov 4	02:05	Maximum for BP1
Nov 4	02:10	Second maximum for BP10
Nov 4	02:10	Start of Jc
Nov 4	02:14	Maximum for BP1
Nov 4	02:19	End of Jc

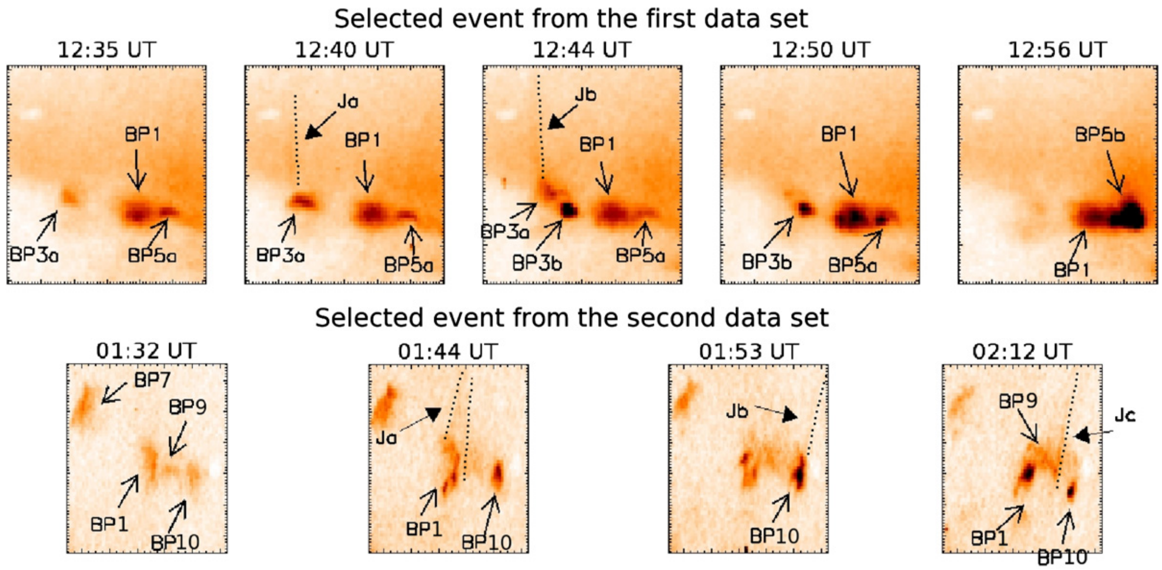

Figure 4. Upper panels: a sequence of images taken on 2007 November 2, by *Hinode*/XRT in the Al_mesh filter, over about 21 minutes, where bright point (BP) brightness fluctuations are apparent and sequentially move through the BP complex. The time sequence of the event is summarized in Table 1, upper panel. To help visualize the two jets occurring over this time interval dotted lines have been drawn onto them (second and third panel). Lower panels: a sequence of images taken on 2007 November 4, by *Hinode*/XRT in the Al_poly filter, over about 40 minutes, where BPs brightness fluctuations are apparent and sequentially move through the BP complex. The time sequence of the event is summarized in Table 1, lower panel. The occurrence of jets is highlighted by dotted lines.

(Animations of this figure are available in the online journal.)

occurrence of X-ray jets, and hence our results are independent of the filter adopted when taking data (and of the contamination the filters might have suffered; Narukage et al. 2011).

Several BPs in this second data set occur over very short periods and have sharp maxima in intensity. After they fade away, occasionally a new BP appears in the same location. BPs observed in the same location have been assigned the same color in Figure 2, but are referred to with different numbers. Furthermore in this second data set, jets from different BPs can occur almost simultaneously: we consider them as components of the same "jet event," and they are referred to with the same number.

As in the previous data set, there are cases where jets appear to be correlated also with local brightness maxima occurring in BPs outside our selected observation box. For instance the jet J4 is also correlated with the brightness maximum at 18:37 UT of a BP located 15″ south and 25″ east of BP2. From the analysis of this second data set we can surmise that six cases out of the six jets events satisfy both point (1) and point (2) of the previous section. Furthermore, three out of the six jet cases are associated with local brightness maxima from more than two BPs. The lower panels of Figure 4 show a sequence from this second data set where BPs sequentially brighten and fade while jets occur, as summarized in Table 1 (bottom section). We conclude that the phenomena seen in the two data sets are consistent and analogous. This suggests that the correlation between jet occurrence and the brightening of multiple BPs is fundamental to the nature of the jets, and both should be accounted for by a common mechanism.

3. RESULTS AND DISCUSSION

The two data sets concur; summarizing the findings: when a jet occurs, there are likely to be multiple X-ray BP intensity fluctuations at the base of the jet.

There may be standard jets/blowout jets within our sample; however, the analysis of individual jets is outside the objectives of the present Letter. Models and ideas for jet formation can, to more-or-less a degree, provide one explanation for the correlation between jet occurrence and BP brightenings. In standard jets, one main X-ray brightening should occur, as in Figure 1 of Moore et al. (2010), which is based on the works of Shibata et al. (1992), Yokoyama & Shibata (1995), and others. For the blowout jets at least one distinct BP is expected, in the same location where it appears in the standard jets (the compact "flare-like" loops formed following reconnection between the emerging bipole and the open field; see Figures 1 and 10 in Moore et al. 2010). Also, an additional X-ray brightening occurs after the bipole blows out and the expelled fields reconnect, but in the examples of Moore et al. (2010) the blown out bipoles have a diffuse nature in XRT images (see their Figures 6 and 8), instead of the rather distinct BPs we observe in this study. Other models for jet formation that do not invoke reconnection energy input have been proposed by Filippov et al. (2009). It is not obvious whether any of the current X-ray jet models can explain correlations that include more than two BPs.

We now present an alternative possible explanation for the apparent propagation of activity among multiple BPs in conjunction with jet formation.

Brightness fluctuation of BPs can result from either the BP area changing with time, and/or because the BP undergoes a variation in temperature (Kariyappa et al. 2011). In actuality, area and temperature changes may be related and naturally result from magnetic field emergence/submergence/reconnection as the agent responsible for the observed modifications. We suggest that gradual BP brightenings, leading to the brightening of a whole BP complex and to minor brightness peaks (see, for instance, the slow brightening of BP1, BP7, and BP10 and the minor peaks in these BPs that occur on November 4 between 00:00 and 04:00 UT), are promoted by gradual phenomena such as flux emergence or flux cancellation, possibly coupled with BP motions and changes in their mutual separations (as sometimes observed in our data) and ensuing gradual reconnection. On the other hand, in this scenario abrupt changes (narrow brightness maxima and/or jets) could be triggered by sudden connectivity changes that occur when some magnetic field stability threshold value is reached. As a consequence, sudden connections to nearby regions are established, and/or extra energy pushes plasma along open field lines.

Our speculation for these field interactions occurring on the relatively small-size and weak-field scales found in polar CHs is motivated by events that have been observed on larger scales. Machado et al. (1988), analyzing flares observed by the Hard X-ray Imaging Spectrometer experiment (Van Beek et al. 1980) on the *Solar Maximum Mission*, came to the conclusion that interaction of magnetic bipoles was essential for triggering flares. According to those authors, there was not a single case, in their data sample, where flares did not encompass "two or more bipoles," and the impulsive phase of flares occurred at the time of rapid spreading of activity over adjacent structures. Also, they argued that gradual evolution of the magnetic configuration leads to gradual changes in the energy of the interacting bipoles. On an even larger scale, Poletto et al. (1993), studying flares within an active region complex, pointed out that intermittent, sequential, sympathetic activity between the two regions of the complex led to flare occurrence. Based on these studies of larger-scale events, we propose that the BP and CH X-ray jet activity observed in our data is the small-scale end of the flare and interacting-region phenomena occurring on active-region size scales. Changes in the connectivity cells (i.e., magnetic regions bounded by separatrix surfaces, e.g., Poletto et al. 1993) induced by the evolution of the magnetic field are at the root of this behavior: interactions among the cells and the ensuing instabilities lead to flares and to a spread of activity over distant locations. This happens on the active-region scale for large-flare events; we are proposing that it also occurs on much smaller scales inside of polar CHs for the BP and X-ray jet events.

Quite obviously, these ideas are speculative at this time, as our current data set, lacking adequate-resolution magnetic data, does not allow investigation of this possibility. This idea is however potentially testable by using simultaneous magnetic field observations with high spatial and temporal resolution; this is a challenging prospect for events near the pole, but may be possible for events occurring within low-latitude CHs, if suitable analogous jets and BPs can be observed there.

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