High-resolution observations of flare precursors in the low solar atmosphere

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Solar flares are generally believed to be powered by free magnetic energy stored in the corona1, but the build up of coronal energy alone may be insufficient to trigger the flare to occur2. The flare onset mechanism is a critical but poorly understood problem, insights into which could be gained from small-scale energy releases known as precursors. These precursors are observed as small pre-flare brightenings in various wavelengths3–13 and also from certain small-scale magnetic configurations such as opposite-polarity fluxes14–16, where the magnetic orientation of small bipole is opposite to that of the ambient main polarities. However, high-resolution observations of flare precursors together with the associated photospheric magnetic field dynamics are lacking. Here we study precursors of a flare using the unprecedented spatiotemporal resolution of the 1.6-m New Solar Telescope, complemented by new microwave data. Two episodes of precursor brightenings are initiated at a small-scale magnetic channel17–20 (a form of opposite-polarity flux) with multiple polarity inversions and enhanced magnetic fluxes and currents, lying near the footpoints of sheared magnetic loops. Microwave spectra corroborate that these precursor emissions originate in the atmosphere. These results provide evidence of low-atmospheric small-scale energy release, possibly linked to the onset of the main flare.

We study the 22 June 2015 M6.5 flare (SOL2015-06-22T18:23) using Hα (line-centre and red-wing) images and photospheric vector magnetograms obtained by the recently commissioned 1.6-m New Solar Telescope (NST)12,13 at Big Bear Solar Observatory (BBSO), which is stabilized by a high-order adaptive optics system (see Methods). In particular, the vector field data are taken by the Near InfraRed Imaging Spectropolarimeter (NIRIS)13 at the 1.56-μm Fe I line. These observations have the highest spatial resolution yet achieved for solar observations (~70 km for Hα and ~170 km for vector field) and rapid cadence (28 s for Hα and 87 s for vector field). Also used are flare microwave spectra and time profiles from the new Expanded Owens Valley Solar Array (EOVSA; see Methods), and time profiles of hard X-ray and soft X-ray fluxes from the Reuven Ramaty High Energy Solar Spectroscopic Imager24 and the Geostationary Operational Environmental Satellite-15, respectively. Ancillary data of full-disk corona images and magnetograms from the Solar Dynamics Observatory (SDO)25 are additionally used.

The long-duration 22 June 2015 M6.5 flare occurred near the disk centre (8°W, 12°N) at NOAA active region 12371. Time profiles of flare emissions in different wavelengths (including hard X-ray, soft X-ray and microwave) clearly show that shortly before the flare impulsive phase starting from ~17:51 UT, there are two short episodes of smaller-magnitude emissions at ~17:24 UT and ~17:42 UT, which we denote as P1 and P2, respectively (see Supplementary Fig. 1). We find that these emissions can only stem from the active region of the imminent M6.5 flare, and that simultaneous Hα brightenings are observed with NST in the flaring core region (see Supplementary Video 1). Thus they can be regarded as precursors of the M6.5 flare. Fine-structural evolution of the associated precursor brightenings in NST Hα and the surface magnetic structure are presented in Fig. 1. Specifically, the brightening associated with the precursor episode P1 first appears as a kernel, P1a, in NST at 17:23:21 UT (also discernible in ultraviolet and extreme ultraviolet; see Supplementary Fig. 2a,d), then quickly turns into an elongated structure with another kernel, P1b (Fig. 1a and Supplementary Fig. 2b). Later, from ~17:38 UT, fine-scale brightening starts to be seen in the south and travels northeastward, apparently along the previously brightened regions in P1. The precursor episode P2 starts around 17:42 UT as kernel P2a (Fig. 1b), and then another, P2b, is formed in the south (Fig. 1c). All the above brightenings exhibit little propagation towards the east. From ~17:46 UT, one of the main flare ribbons, Fa, seems to develop from the P2a region (see Fig. 1d and Supplementary Video 1).

Regarding the precursor brightenings, we notice that P1a/P1b and P2a/P2b all lie along a narrow lane of largely positive magnetic polarity, a few arcseconds to the east of the magnetic polarity inversion line (PIL) (see Fig. 1e). The region of P1a is co-spatial with small-scale mixed polarities (discussed below) located near the footpoints of large-scale sheared arcades, which are approximately illustrated as L1 and L2 in Hα and 193 Å (see Fig. If and Supplementary Fig. 2d,e). Some other brightenings are seen near the southern footpoint of L2 in the negative field region (see, for example, Supplementary Fig. 2a–d). Furthermore, precursor brightenings predominantly move along (parallel to) the PIL, in contrast to the separation motion of the main flare ribbons Fa and Fb (see Fig. 1d, Supplementary Fig. 2c, and Supplementary Video 1) away from the PIL, which complies with the standard flare model26.

In Fig. 2, we present the NIRIS vector magnetic field measurement of the flare core region. The magnetic field is highly sheared...
with respect to the PIL, especially in the precursor brightening region (Fig. 2a,b). This signifies a high degree of non-potentiality, as reflected by the concentration of magnetic shear along the PIL (Fig. 2c; see equation (1) in Methods). In the region around the initial precursor brightening P1a (enclosed by the box in Fig. 2b), we observe elongated, alternating positive and negative polarities on a fine scale of ~3,000 km, constituting a miniature version of the magnetic channel structure also recognized as the opposite-polarity type field (see also Supplementary Video 2). Importantly, both the negative and positive fluxes within the channel exhibit an increase (by about ~6.6 × 10^{14} and 9.3 × 10^{14} maxwell (Mx), respectively, in about half an hour) temporally associated with the occurrence of the precursor episodes P1 and P2, and a decrease after the peak of the flare non-thermal emission (Fig. 2d). These imply that the dynamic evolution of the magnetic channel region is closely related to the triggering and subsequent evolution of the flare. It is possible to find the spatial and temporal correlation between the appearance of the precursor brightenings and the properties of the magnetic field structure and evolution because of the high spatial and temporal resolution of the NIRIS data.

We further characterize the fine-scale properties of the magnetic channel region in Fig. 3. A comparison reveals that the precursor brightenings P1a/P1b (Fig. 3a) appear in the vicinity of regions of strong vertical current density (curl of the horizontal field; calculated from equation (2) in Methods and shown in Fig. 3c), similar to what has been found previously for main flare ribbons (for example ref. 25). We also place a slit right across the magnetic channel and plot the profiles of the vertical magnetic field and current density along it (black dashed and red solid lines, respectively, in Fig. 3d). The results show ~5 (11) time reversals of magnetic polarity (electric current) within ~3,000 (6,000) km, demonstrating the complexity of this channel region at small scales. The profiles of Hα + 1.0 Å along the same slit (blue dotted line in Fig. 3d) shows that the brightening has a fine structure on a scale of 500 km or less. Similar to the magnetic flux, the unsigned vertical electric current integrated over the channel region shows a clear increase (by ~5 × 10^{12} A in about half an hour) closely related to the timing of precursors P1/P2, and also a decrease after the main energy release (Fig. 2d). Such a flare-related evolutionary pattern is not found in other areas within the observed field of view. These results are suggestive that the enhancing magnetic channel structure corresponds to an emerging small current-carrying flux tube, which might be dissipated by reconnection with ambient fields after the flare.

To extend the measurement of the magnetic field to the three-dimensional (3D) domain, we turn to the analysis of microwave observations. For reasonably uniform emission sources (such as flare precursors), the magnetic field can be derived from the total power data28. In Fig. 4a, the EOVSA total-power dynamic spectrum (intensity recorded in a time-frequency diagram, averaged from the measurements of 20 dishes), with the preflare quiet Sun and active-region contribution subtracted, shows microwave flaring emissions of the two precursor episodes P1/P2 and the impulsive phase.
Our analyses show that the microwave spectra in the precursor periods can be modelled as quasi-thermal, gyrosynchrotron emission sources (for example Fig. 4b,c; see Methods). Their instantaneous spectral shape is determined by several physical parameters, including temperature, magnetic field and electron density. For our purposes, we consider the temporal evolution of only the magnetic field during the precursor periods, which is derived from the spectral fittings and plotted in Fig. 4d,e. The magnetic field strengths of precursors P1 and P2 are strong ($\gtrsim 1,000$ G) at the beginning, then gradually decrease to a lower level (500 and 300 G, respectively). Based on the relationship between the average magnetic field strength and height above the surface as suggested by a non-linear force-free field (NLFFF) extrapolation model of this flaring region (see Methods and Supplementary Fig. 3b), this result indicates that both precursor emissions are initially located in the low atmosphere (at photospheric/chromospheric level), which corroborates the NST analysis.

Taken together, BBSO/NST H$_\alpha$ images complemented by EOVSA microwave observations identify the low-atmospheric precursor emissions in close relation to the onset of the main flare. We propose that the present event proceeds in a way consistent with the model of ref.14: an emerging small-scale flux tube, as signified by the strengthening magnetic channel of opposite-polarity type 14, interacts with and aids the reconnection of the ambient legs of large-scale sheared loops rooted in major polarities (Supplementary Fig. 2d), producing precursor brightenings. These sheared loops are also demonstrated by the NLFFF model (Supplementary Fig. 3a), in which they lie close to the surface with an apex height of $\sim 5$ Mm. The reconnection site between the small-scale emerging flux and sheared arcades is located at the photospheric/chromospheric level; subsequently, the accelerated particles can quickly propagate and cause brightenings in other remote footpoints (for example P1c in Supplementary Fig. 2a,b,d). During the two precursor periods, the motion of H$_\alpha$ brightening kernels along the PIL may reflect the successive reconnection of different branches of the sheared arcade loops, which eventually leads to the imminent eruption of the main flare (Supplementary Fig. 2f). We made no attempt to compare our observations with other flare triggering scenarios, as

**Figure 2 | Magnetic field structure and evolution.** a, b, BBSO/NST NIRIS photospheric vertical magnetic field (scaled between ±1,500 G) at 17:35:30 UT superimposed with arrows (for clarity, those in positive/negative fields are coded in blue/red) representing horizontal magnetic field vectors. The box in a (same as those in Fig. 1a,b,e,f) denotes the field of view of b, in which the magnetic channel structure can be clearly observed. c, Distribution of magnetic shear (see Methods). The overplotted yellow contour in a–c is the PIL. d, Temporal evolution of total positive (blue dotted line) and negative (red solid line) magnetic fluxes and the unsigned electric current (black dashed line; see Methods), calculated over the magnetic channel region enclosed by the box in b. The plotted representative error bars correspond to 1 s.d. calculated over the post-flare period 18:50 to 19:40 UT, demonstrating the background variation. The first two vertical dashed lines indicate the times of precursor episodes P1 and P2 at 17:24 and 17:42 UT, respectively; the third vertical dashed line denotes the peak time of the flare non-thermal emission in microwave at 17:58 UT (see Supplementary Fig. 1).
the model of ref. 14 is perhaps the only one that incorporates both the small- and large-scale magnetic structures (that is, small opposite-polarity type field and overlying sheared arcades). As sheared arcade systems are often present in flaring active regions, more observations of the low solar atmosphere, especially high-resolution photospheric magnetic field measurements with good temporal coverage, are desirable. This would allow the problem of the flare onset mechanism to be better understood, as is needed for improving forecasts of space weather.

Methods

Optical wavelength observations and reduction. The NST is a 1.6-m off-axis telescope at BBSO operated by the New Jersey Institute of Technology. Currently, it produces the highest-spatial-resolution (for example, 70 km when observing around 6,000 Å), diffraction-limited observations of the Sun, aided by a 308-element adaptive optics system and speckle-masking image reconstruction. During the period of ~16:50–23:00 UT on 22 June 2015, NST observed the M6.6 flare at NOAA AR 12371. The data taken include spectroscopic observations in Hα line centre and ±0.6 and ±1.0 Å (with a bandpass of 0.07 Å), and also images in the TIO band (a proxy for the continuum photosphere around 7,057 Å). The images have a spatial resolution of ~70–80 km and a cadence ranging from 15 to 28 s.

Notably, this study makes the first scientific use of data from NIRIS, which measured the photospheric magnetic field during this observation run. This is also NIRIS’s first coverage of a flare observed with NST. NIRIS uses dual Fabry–Pérot etalons that provide a 60,000 km x 60,000 km field of view and a great throughput of over 90%. NIRIS achieves a spatial resolution of ~170 km at the 1.56-μm Fe i line (with a bandpass of 0.1 Å). The cadence of NIRIS data (full set of vector magnetograms) for this 22 June 2015 observation run is 87 s.

The 1.56-μm line offers a high Landé g-factor of 3, which can help to increase the signal strength of magnetograms. Although this line has a lower diffraction order (full set of vector magnetograms) for this 22 June 2015 observation run is 87 s. NIRIS achieves a spatial resolution of ~170 km at the 1.56-μm Fe i line (with a bandpass of 0.1 Å). The cadence of NIRIS data (full set of vector magnetograms) for this 22 June 2015 observation run is 87 s.

For this 22 June 2015 observation, we validate the NIRIS data by checking against those obtained from two spaceborne instruments, the spectropolarimeter (SP) of Hinode’s 0.5-m Solar Optical Telescope16 and SDO’s Helioseismic and Magnetic Imager (HMI)2. Hinode/SP and SDO/HMI have spatial resolutions of about 230 and 725 km, and temporal cadences of a few hours and 12 minutes, respectively. In Supplementary Fig. 4, we compare line-of-sight field, transverse field and azimuthal angle measurements from the three instruments measured around 22 June 2015 22:35 UT. It can be clearly seen that the magnetic structures observed by NIRIS, Hinode/SP and SDO/HMI are highly similar, but more details are present in NIRIS data, owing to its higher spatial resolution. A cross-correlation analysis reveals that data acquired by NIRIS match well with those taken by Hinode/SP and SDO/HMI, with correlation coefficients of 0.97, 0.9 and 0.8 for the line-of-sight field, transverse field and azimuthal angle measurements, respectively. This demonstrates the superiority of NIRIS observations in making high-spatiotemporal-resolution studies of photospheric magnetic field evolution.

Third, to explore the magnetic field structure properly, we further process the NIRIS vector magnetograms resulting from inversion, to resolve the 180° azimuthal ambiguity using the ME0 code17, which is based on the ‘minimum energy’ ambiguity resolution method18,19, and to remove the projection effects by transforming the observed vector fields (line-of-sight and transverse) to those in heliographic coordinates (vertical $B_z$ and horizontal $B_x$ and $B_y$ fields) using the equations of ref. 20. To characterize the non-potentiality of the active region, we calculate magnetic shear $S$, defined as the product of field strength and shear angle21,22:

$$S = \mu_0 \theta$$

(1)

where $\theta = \cos^{-1}\left(\langle B_z \rangle / |<B_z>|\right)$, and the subscript $p$ represents the potential field (here computed using the Green’s function method21). We also derive the vertical current density $J_z$:

$$J_z = \frac{1}{\mu_0} \frac{\partial B_z}{\partial z} = \frac{1}{\mu_0} \frac{\partial B_z}{\partial x} - \frac{\partial B_y}{\partial y}$$

(2)

where $\mu_0$ is the permeability of the vacuum.

Full-disc observations for context. We complement high-resolution NST data with full-disc SDO observations for a better understanding of the overall picture of the flare. Images shown in Supplementary Fig. 2 include those from SDO’s Atmospheric Imaging Assembly23, 1,700-Å (temperature minimum region and photosphere), 193-Å (corona and hot flare plasma) and 94-Å (hot flare plasma) passbands, and SDO’s HMI.

Microwave observation and analysis. This study also makes the first scientific use of the EOVSA data. EOVSA is a newly upgraded, solar-dedicated radio array consisting of 13 antennas of 2.1-m diameter, which are equipped with receivers designed to cover the frequency range 1–18 GHz. Two large (27-m diameter) dishes are being outfitted with He-cooled receivers for use in calibration of the small dishes24. EOVSA has just started scientific operation.
For the event under study, the EOVSA microwave observation covers both the precursors and the main flare. Although the microwave spectrum is broadband during the main flare (which is a result of source non-uniformity in space), the preflare phase demonstrates reasonably narrow spectra consistent with a quasi-uniform source. This kind of source can be conclusively forward-fitted using the gyrosynchrotron source function to recover the physical parameters responsible for the observed spectral shape. Inspection of the detailed spectral shape at the preflare phase reveals that the spectra are almost thermal, which greatly simplifies the fitting and enhances the reliability of the fit results. To define the gyrosynchrotron source function quantitatively, we use the fast gyrosynchrotron codes developed in ref. and apply the optimization scheme as described in ref. The fit returns evolution of the plasma density, temperature and magnetic field strength (as shown in Fig. d,e). In this analysis, we focus on the evolution of magnetic field at the instantaneous location of the radio burst, which recovers a significant elevation of the radio source with time and thus allows us to extend the analysis to the 3D domain. The use of a magnetic field extrapolation model (see below) maps the coronal magnetic field probed from the microwave data to the actual heights above the active region.

**Coronal magnetic field extrapolation.** To disclose the magnetic structure above the flaring active region, we use the NLFFF extrapolation technique to construct a 3D magnetic field. As NIRIS data have a limited field of view, we base the magnetic field modelling on the lower-resolution SDO/HMI vector data. A preprocessing procedure is first performed to minimize the net force and torque in the observed photospheric field. A weighted optimization method is then applied to derive the NLFFF from which magnetic field lines are computed. Physical properties of field lines, such as the magnetic twist, can be further deduced.
