Zhao et al. Geoscience Letters (2022) 9:36
https://doi.org/10.1186/s40562-022-00245-8

Geoscience Letters

RESEARCH LETTER

Open Access

Auroral responses to the visit of comet 73P/Schwassmann–Wachmann 3 in 2006

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Abstract

The stunning tails of comets are interesting astronomical phenomena to human beings and have been noticed for thousands of years. The bright tails also emit substantial materials into interplanetary space, including dusts and charged particles. The charged particles are picked up by solar wind magnetic fields, and thus could propagate together with solar wind to influence planetary space environments. Simultaneous measurements of comet materials, planetary space, and ground environments are crucial for understanding cometary impacts to planets, while such observations are quite rare. In this article, we present a full chain from the comet tail, to the solar wind cometary particles, and the impacts on the ground. Intense auroral events are observed when the cometary materials are observed in the Earth's upstream solar wind. Our results provide direct evidence that cometary ions could contribute substantial dynamic pressure in driving geomagnetic activities and the associated auroral intensifications.

Introduction

The Sun is constantly interacting with solar system bodies in multiple dimensions. Solar radiation and solar wind are two major energy sources to drive these interactions (Thomas 1978; Kerker 1981). In our solar system, most planets have global magnetic fields (i.e., Mercury, Earth, Saturn, Jupiter, Uranus, and Neptune), as a result of electrically conducting, convecting, and rotating interior cores. For the planets with global intrinsic magnetic fields, it is known that the solar wind particles would shape these planetary magnetic fields and thus form global magnetospheres (Spreiter et al. 1966; Russell 1972; Delamere et al. 2014). Meanwhile, solar radiation could ionize their atmospheres, with an exception of Mercury, forming ionospheres for these planets (Breus et al. 2004). The planet with a magnetosphere and an ionosphere, such as our Earth, would have a dynamic electrical current system between the magnetosphere and ionosphere, and it would cause magnetic perturbations on planetary grounds (Boström 1964; McPherron et al. 1973; Nakata et al. 2000). Take the Earth as an example, the coupling processes of magnetosphere and ionosphere, during geomagnetic storms or substorms are highly dynamic and thus produce strong perturbations on the magnetic field and energetic particles (Akasofu 1964, 2021).

Besides the planets with global magnetic fields, the solar radiation and solar wind could also have strong interactions with the solar system bodies without a global magnetic fields, including Mars, Venus, asteroids, and comets. Mars and Venus have global ionospheres due to solar radiation, and thus interact with solar wind to form induced magnetospheres (Bertucci et al. 2011). Solar radiation could produce a substantial atmosphere and further ionize the atmospheric neutral atoms to form an ionosphere, which interact with solar wind to form a magnetosphere for a comet (Nilsson et al. 2015).

The interaction between solar wind and a comet not only produces dynamic processes near the comet, but also has significant influence on the interplanetary space environment (Holmstrom and Wang 2015; McKenna-Lawlor et al. 2016), and sometimes leads to important impact on solar system planets. When a comet

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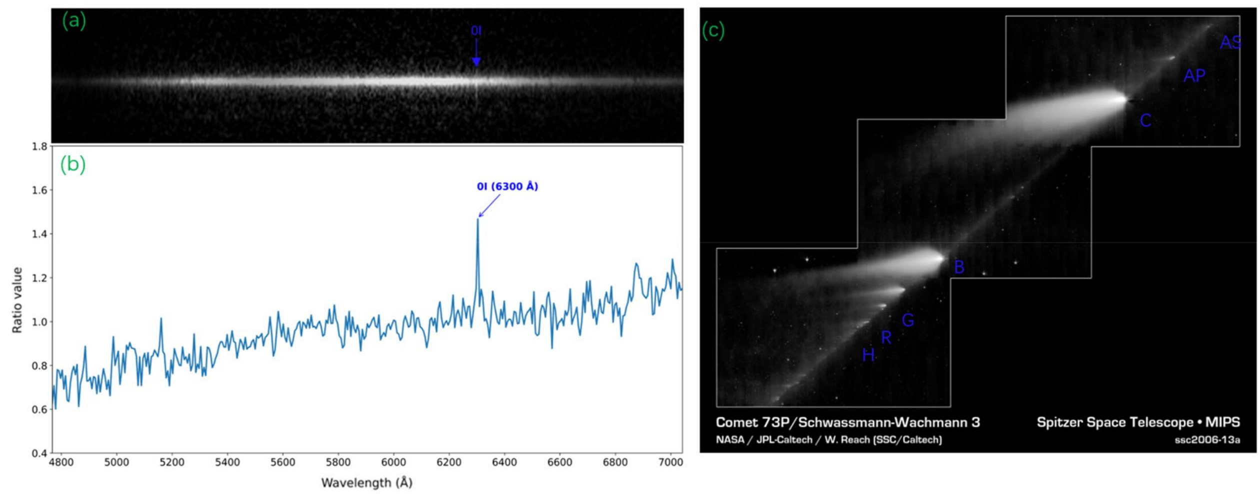

Fig. 1 **a**: Optical spectrum of the comet 73P-C/ Schwassmann–Wachmann 3 after sky removal. **b**: Ratio of the comet 73P-C/Schwassmann–Wachmann 3's spectrum and of the HD 197076's spectrum. The data for **a** and **b** are both from http://www.astrosurf.com/buil/sw3/result.htm. **c**: Identification of the fragments of the comet 73P-C/Schwassmann–Wachmann 3 taken by the Spitzer Space Telescope in 2006 May. The meteoroid stream is clearly visible and seems to "connect" the fragments

approaches the Sun, some of its materials are volatile and sublimate into interplanetary space. The cometary O^+ ions are picked up by solar wind and thus could propagate with solar wind to the terrestrial magnetosphere (Wenzel et al. 1986). The mass release into interplanetary space could be substantial at the Earth–Sun distance, which is why we can often see bright cometary tails from the ground. In October 2014, the comet Siding Spring (C/2013 A1) had a close passage by Mars, and led to a temporary planet-wide ionospheric layer below Mars' main dayside ionosphere (Schneider et al. 2015). On the other hand, the cometary ions are believed to have very different impacts on Earth, which has a global magnetic field. The detection of the interaction between cometary particles and the terrestrial magnetosphere is rare. It is believed that the passage of the comet Halley in 1910 May caused small geomagnetic activity, although the direct detection of this interaction in space was not possible at that time (Russell et al. 1988).

In this article, we detail a geomagnetic event with unprecedented conjugate observations of the comet 73P/Schwassmann–Wachmann 3. The event provides new insights into the understandings of how comets influence planetary atmospheres, particularly our Earth. We present a possible correlation from the comet's tail materials, to solar wind environment, to the terrestrial geomagnetic fields, and auroral emissions.

Data and results

The comet 73P/Schwassmann–Wachmann 3 is a member of the Jupiter family of short-period comets, with an orbital period of 5.4 yr and it was discovered on May 2 1930 by Arnold Schwassmann and Arno Wachmann at the Hamburg (Germany) observatory. In 1995, the comet began to break up into five fragments (Sekanina 2005). During the comet's return to perihelion, it experienced several outbursts, and broke up into many pieces. From the observation of the Subaru 8.2 m telescope, no fewer than 154 minicomets were detected (Ishiguro et al. 2009).

Figure 1a presents the optical spectrum of the comet 73P-C/Schwassmann–Wachmann 3 after sky removal, which was observed by Celestron 11 + Lhires III #76 spectrograph[1] on May 10 2006. The blue line is the neutral atomic oxygen line at 6300 Å. The ratio of the comet 73P-C/Schwassmann–Wachmann 3's spectrum and of the HD 197076's spectrum is shown in Fig. 1(b). Figure 1(c) shows the mosaic of images, revealing many fragments of the comet 73P/Schwassmann–Wachmann 3, which was taken by the Spitzer Space Telescope in May 2006.

Gilbert et al. (2015) showed for the first time, in situ ion measurements of the comet 73P/Schwassmann–Wachmann 3 from ACE/SWICS (Stone et al. 1998) and Wind/STICS (Wilson et al. 2021). ACE and Wind are satellites located at Lagrange point (L1) in the Sun–Earth system, to monitor Earth's upstream solar wind condition. A

[1] http://www.astrosurf.com/buil/lhires3/project.htm.

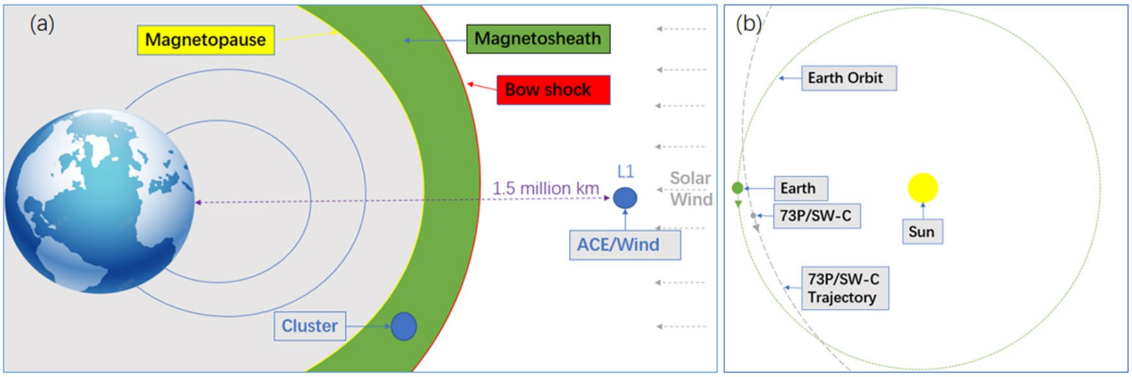

Fig. 2 **a**: A schematic of geometry (not to scale) shows the location of ACE/Wind satellites. The ACE and Wind are satellites located at Lagrange point (L1) in the Sun–Earth system. **b**: A top view of a schematic of geometry (not to scale) shows the location of the Sun, Earth, and fragment C of the comet 73P/Schwassmann–Wachmann 3 on May 31 2006. The directions of motion of the Earth and comet are also marked in the figure

schematic of geometry (not to scale) shows the location of ACE/Wind is shown in Fig. 2(a). Meanwhile, a top view of a schematic of geometry (not to scale) shows the location of the Sun, Earth, and fragment C of the comet 73P/Schwassmann–Wachmann 3 on May 31 2006, as shown in Fig. 2(b). The plasma velocity at ACE or Wind was expected to mainly move toward the Earth. Therefore, the O^+ detected by ACE or Wind would have arrived at the Earth in about 1 h. Since this study is about day-to-day variation, the time delay of 1 h has little influence on our analysis.

Besides the focus on the comet (Gilbert et al. 2015), we here analyze the relationship between solar wind and cometary material. The solar wind parameters were obtained from the National Space Science Data Center (NSSDC) through the OMNIWEB database.[2] Meanwhile, we also analyzed the auroral images during this time. For the auroral images data, we obtained this from the Special Sensor Ultraviolet Spectrographic Imager (SSUSI) on board the Defense Meteorological Satellite Program (DMSP F16[3]; wavelength of 121.6 nm). For DMSP data processing, we superimposed the data of all orbits from each day according to the method of averaging the same position. In this study, we only investigate auroral variation longer than daily variations, so that the auroral processing method is good enough for the present investigation.

Figure 3 shows the solar wind properties (including magnetic field magnitude, slow wind speed, and flow pressure) and cometary O^+ flux during May 23 2006–June 17 2006. The data of O^+ flux are from Gilbert et al. (2015). The O^+ flux in Fig. 3(e) is measured by the ACE/SWICS at energies of 0.6–83 keV/e. The O^+ fluxes have been shifted to the Earth'sbow shock by assuming that the solar wind speed is constant from the ACE spacecraft to Earth.

As shown in Fig. 3(a–c), there are two fast streams in the solar wind. A stream interaction region (SIR) is a region of compressed plasma formed when a fast solar wind stream overtakes the preceding slower solar wind stream. In the middle of an SIR is a stream interface separating slow streams and fast streams, where the total pressure reaches its maximum (e.g., Jian et al. 2006). As the SIRs propagate away from the Sun, their boundaries will steepen and probably form shocks at one astronomical unit or beyond (e.g., Richardson lan 2018). The SIR-related shocks can accelerate charged particles efficiently (e.g., Richardson Ian 2004, and references therein). More than 50% of the SIRs can cause geomagnetic activity (e.g., Zhang et al. 2008; Sanchez-Garcia et al. 2017; Chi et al. 2018). Two large pressure enhancements were observed during the two SIRs as shown in Fig. 3d. The enhancements of cometary O^+ flux were also observed in solar wind (Fig. 3e). It is mysterious that the cometary O^+ particles are highly concentrated in SIRs.

Figure 4 shows the sequence of southern hemisphere auroral images of the Earth during May 23 2006 to June 17 2006. There are two massive auroral intensifications on May 30 and June 6, which are consistent with the observed SIRs and the enhanced cometary O^+ in the solar wind. On June 15, there was a slight enhancement in pressure (Fig. 3d), corresponding to an auroral intensification.

Figure 5 presents the changes of the Auroral Electrojet (AE) index, DST index, O^+ flux, and two aurora enhancements, DST index, O^+ flux, and two aurora

[2] https://cdaweb.gsfc.nasa.gov/pub/data/omni/omni_cdaweb/.

[3] https://ssusi.jhuapl.edu/data_availability?spc=f16&type=edr-aur.

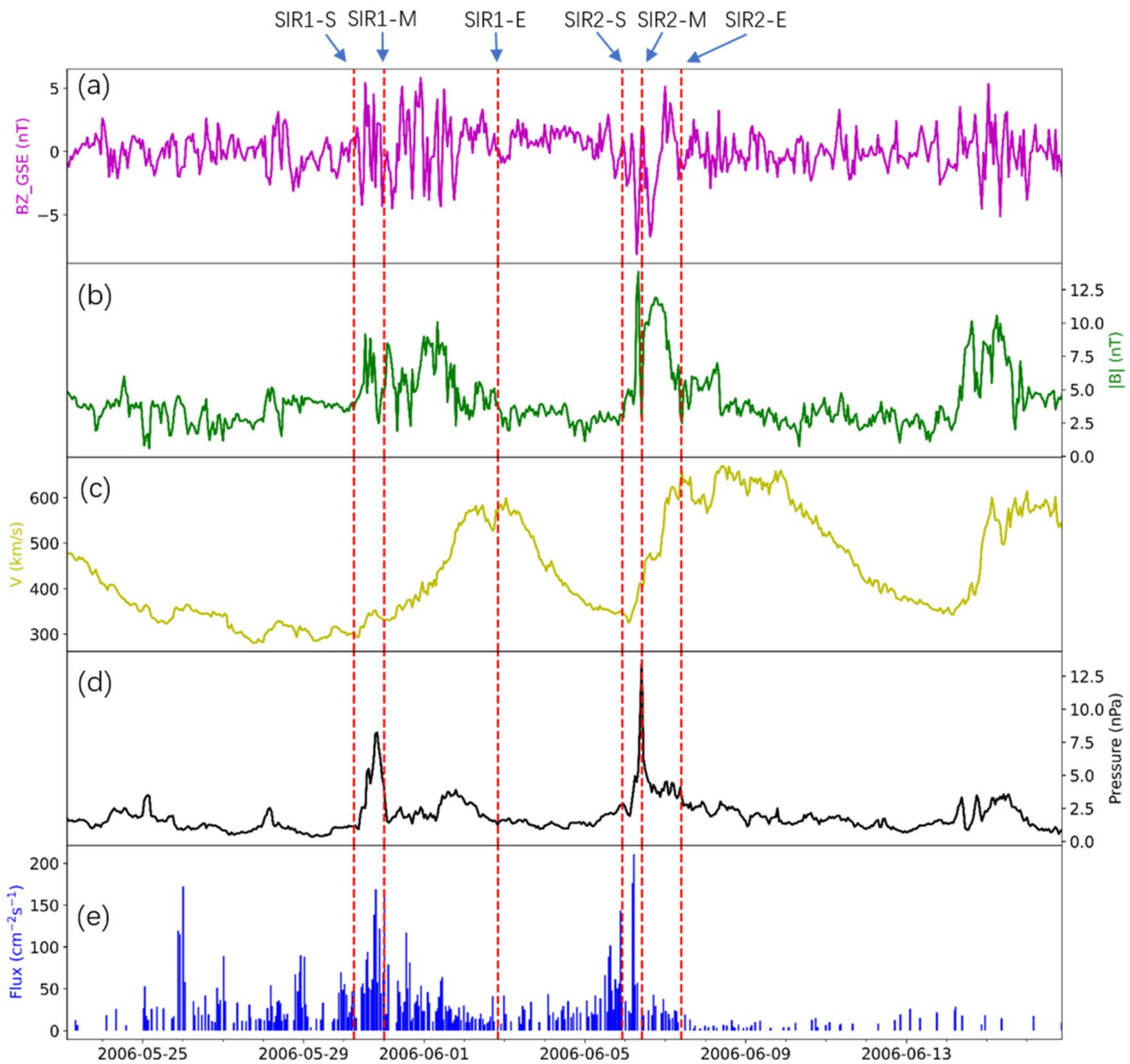

Fig. 3 The solar wind properties and cometary O^+ flux during May 23 2006–June 17 2006. **a**, **b** Show the magnetic feild magnitude (nT). **c** Shows the wind speeds (km s^{-1}). **d** Shows the flow pressure (nPa). **e** Gives the cometary O^+ flux (cm^{-2} s^{-1}) from Gilbert et al. (2015). The vertical lines are the start, middle, and end moments of two SIR events

enhancements during May 23 2006 to June 17 2006. The correlation among the DST, AE, cometary O^+ flux, and auroral intensification are obvious. Two major perturbations are on May 30 and June 6.

Discussion and summary

The study provides important evidence for the connection between a comet and a planetary magnetosphere, and the consequent planetary space weather (e.g., geomagnetic storms). Geomagnetic storms are known to produce strong perturbations of electrical currents and energetic particles in the terrestrial magnetosphere and ionosphere (Dobrica et al. 2016; Blagoveshchenskii 2013), threatening facilities on the ground and in space, such as satellites (Möstl et al. 2010) and ground power grids (Carrington 1859; Liu et al. 2013). Geomagnetic storms are known to be strongly controlled by solar activities and solar wind conditions. In fact, Carrington discovered the connection between solar activity and auroral emissions in an unusually powerful solar flare on record in 1859 (Carrington 1859). The solar event in 1972 between the Apollo 16 and 17 missions was the strongest in recorded history (Russell et al 2017; Knipp et al. 2018). The event exploded sea mines off the coast of Vietnam, and it arrived even faster than the Carrington event, when corrected for angle of the flare from the Earth–Sun line location. The influence of cometary materials on the Earth or other planets is rarely investigated due to limited

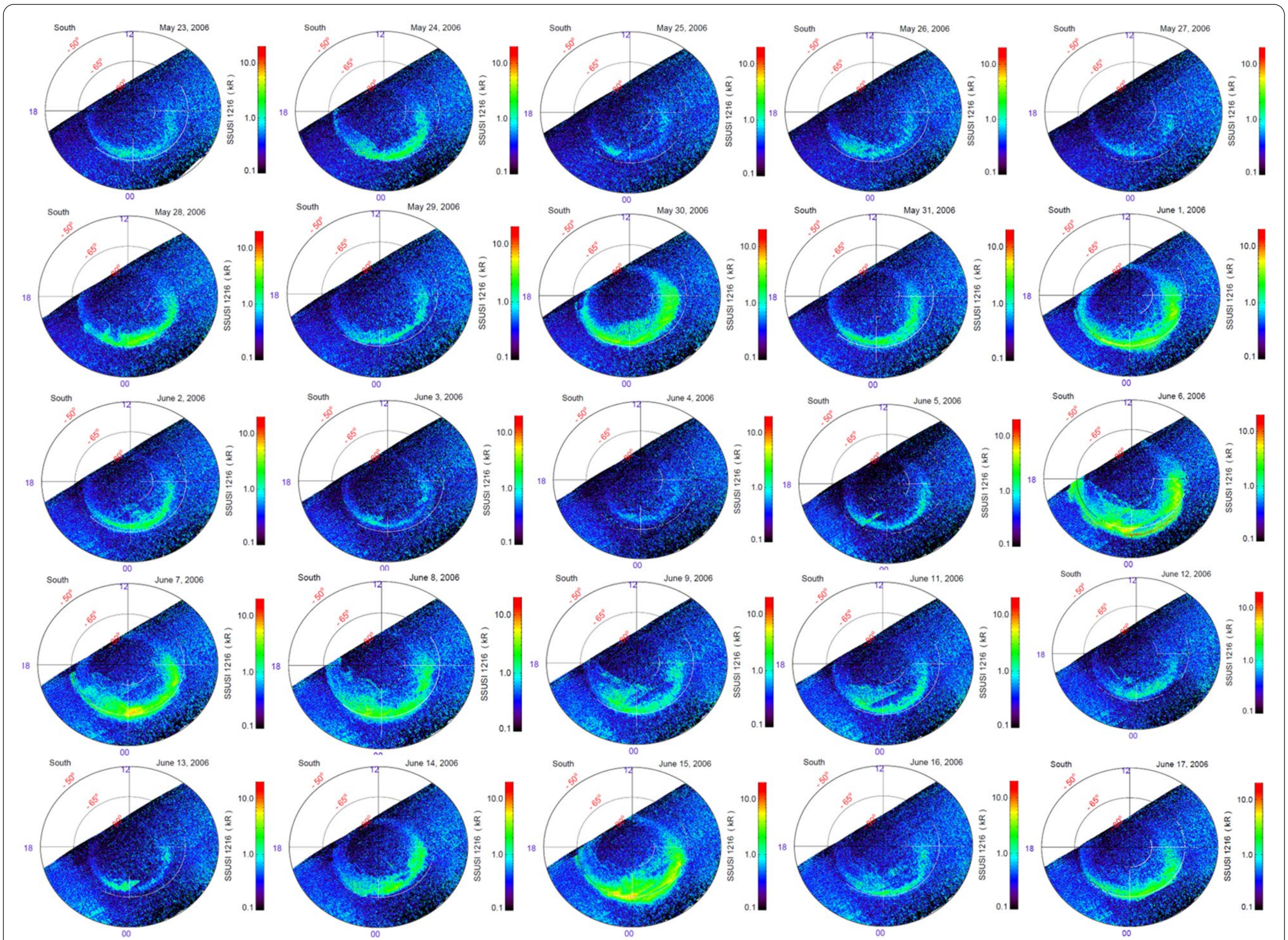

Fig. 4 The auroral sequence taken by DMSP–SSUSI during May 23 2006–June 17 2006. Each auroral image consists of all southern auroral images taken above the South Pole

observations. As more and more electronic devices are being used nowadays, we need more than ever, to better characterize space perturbations. Thus, the understanding of comets' influence on terrestrial space would become more and more useful.

In this study, O^+ is detected in the comet's tail and the solar wind, clearly indicating that the comet could provide important particles to the near-Earth interplanetary environment. It is quite surprising that the cometary particles were highly concentrated in the SIR magnetic flux tube, although the mechanism remains unknown. The processes leading to the particle concentration deserve further investigation; nevertheless, the consequence of particle concentration may tell us that cometary materials may have significant impact on a planet. The cometary ions could potentially have high density (Glassmeier 2017) in the tail. The high-density cometary ions are rapidly picked up by solar wind to high speed and somehow concentrated by solar wind magnetic structure. Therefore, the heavy ions could potential enhance solar wind dynamic pressure to Earth's upstream, which then directly compress the magnetosphere to drive geomagnetic storms or substorms.

Comets are active celestial bodies that can eject substantial amount of dust and charged particles when approaching the Sun. The influence of cometary materials to interplanetary space and the inner solar system planets is far from well understood. The spacecraft orbiting the Sun (e.g., Solar Orbiter) could significantly improve the understanding of cometary materials from in situ measurements (Matteini et al. 2021). Moreover, particle simulation, together with in situ and remote sensing observations, could be very helpful to improve the space perturbations caused by cometary materials in inner solar system space and planetary environments.

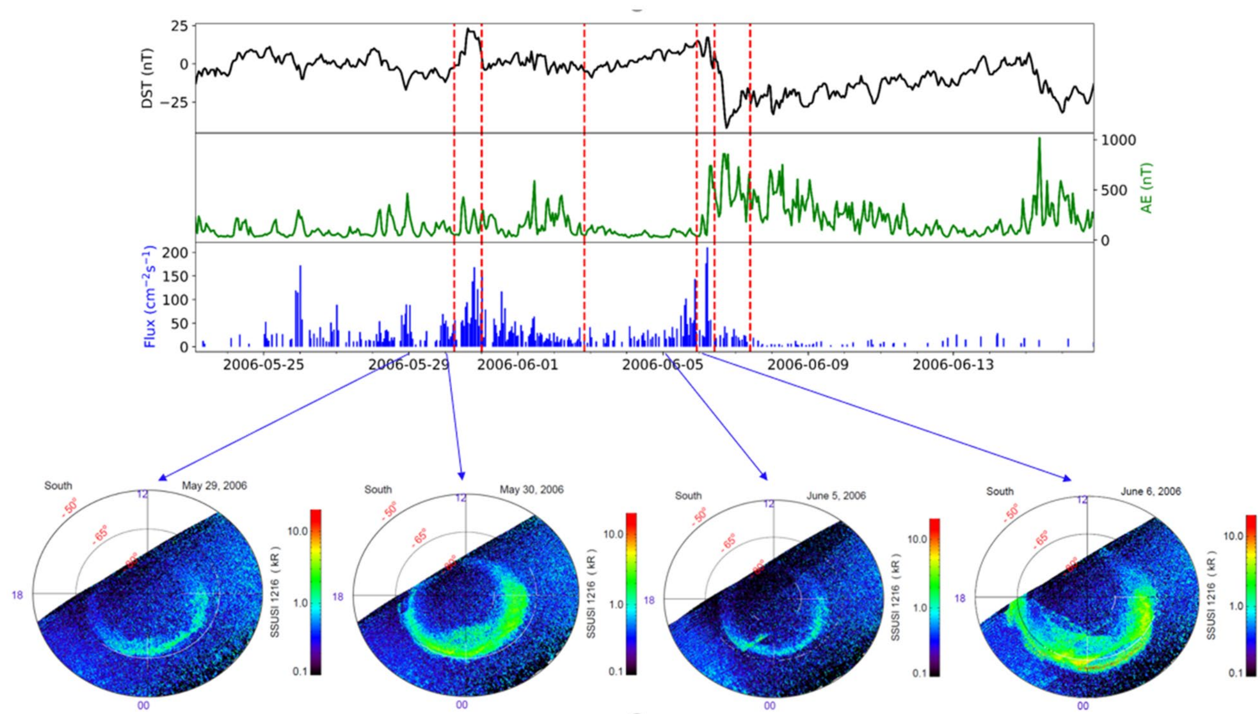

Fig. 5 The changes of the Auroral Electrojet (AE) index, DST index, O^+ flux, and two aurora enhancements during May 23 2006–June 17 2006. Same as Fig. 3, the vertical lines are the start, middle, and end moments of two SIR events

Acknowledgements
The spectrum of the comet 73P-C/Schwassmann–Wachmann 3 in this study is available at http://www.astrosurf.com/ buil/sw3/result.htm. The DMSP data in this study are from https://ssusi.jhuapl.edu/data_availability? spc=f16&type=edr-aur. We also acknowledge NASA's Space Physics Data Facility (SPDF) for providing OMNI data (https://omniweb.gsfc.nasa.gov/).

Author contributions
ZHY and YW designed the investigation. YZ and LMY performed the major data analysis and paper draft. RLG, HRL and BZZ helped data analysis and the interpretations. All authors read and approved the final manuscript.

Funding
This work was supported by the National Science Foundation of China (grant 42074211) and Key Research Program of the Institute of Geology & Geophysics CAS (grant IGGCAS-201904). The authors wish to thank the International Space Science Institute in Beijing (ISSI-BJ) for supporting and hosting the meetings of the International Team on "The morphology of auroras at Earth and giant planets: characteristics and their magnetospheric implications", during which the discussions leading/contributing to this publication were held. L.Y. was supported by the Youth Innovation Promotion Association of CAS (2021064).

Availability of data and materials
The spectrum of the comet 73P-C/ Schwassmann–Wachmann 3 in this study is available at http://www.astrosurf.com/buil/sw3/result.htm. The DMSP data in this study are from https://ssusi.jhuapl.edu/data_availability? spc = f16&type = edr-aur. We also acknowledge NASA's Space Physics Data Facility (SPDF) for providing OMNI data (https://omniweb.gsfc.nasa.gov/). The plasma data from ACE satellite were taken from Gilbert et al. 2015. Geomagnetic data (i.e., AE, DST index) were taken from World Data Center for Geomagnetism, Kyoto via https://wdc.kugi.kyoto-u.ac.jp/.

Declarations

Ethics approval and consent to participate
The authors would like to confirm that they have no competing interest regarding this paper. All authors worked closely on this project starting from the conception of the project through modeling, analysis, interpretation of the results and write-up of the manuscript.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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Received: 29 July 2022 Accepted: 30 August 2022
Published online: 15 September 2022

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