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ISOLATED SUNSPOT WITH A DARK PATCH IN THE CORONAL EMISSION

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Abstract. On the base of the 17 GHz radio maps of the Sun taken with the Nobeyama Radio Heliograph we estimate plasma parameters in the specific region of the sunspot atmosphere in the active region AR 11312. This region of the sunspot atmosphere is characterized by the depletion in coronal emission (soft X-ray and EUV lines) and the reduced absorption in the a chromospheric line (He I 1.083 μm). In the ordinary normal mode of 17 GHz emission the corresponding dark patch has the largest visibility near the central solar meridian. We infer that the reduced coronal plasma density of about $\sim 5 \times 10^8$ cm^{-3} is the characteristic feature of the dark patch.

Key words: Sun: radio emission, corona, magnetic fields

1. INTRODUCTION

The problem of the formation and acceleration of the outward plasma flow of the solar wind is of importance in solar-terrestrial relations. Coronal holes (CHs) are proved to be the regions of open magnetic fields and the origins of solar wind. Recent observations with the Extreme- Ultraviolet Imaging Spectrometer aboard the satellite Solar-B point to the specific role of the closed magnetic structure, which neighbors the open one, in the acceleration of plasma flow at the boundary of a CH.

Obridko and Shelting (1999) noted an analogy between the coronal holes and the large isolated sunspots: the vertical magnetic field configuration and the drop of plasma density seem to be the common properties. According to this analogy, if a part of the atmosphere of the isolated sunspot resembles the “coronal hole”, the CH/AR boundary should be the region of the plasma outflow (Bilenko 2005). As noted by Koutchmy & Le Piouffle (2008), the isolated sunspots have been neglected for years due to an apparently simple structure: “Indeed today solar physicists concentrate their attention to sunspot regions and active centers, and the systematic observation of single “unipolar” and quasi-symmetric sunspots is widely neglected, although theoreticians like to consider a single sunspot when they discuss the details of their physics, especially when the umbral core and the penumbral filaments are analyzed".

It is well established that the microwave source associated with a large isolated sunspot shows low radio brightness in the ordinary (o-) mode at the centimeter wavelength as short as 1.76 cm (see Grebinskij et al. 1998). While the radio brightness in the extraordinary (x-) mode is about 100 times brighter than the quiet Sun, the brightness in the o-mode can be ~ 2 times fainter. This low brightness at short centimeters is traced to the low plasma density in the region of the sunspot atmosphere which appears to be dark in the soft X-ray emission and becomes brighter in the infrared He I absorption line. All these features are characteristics of a CH (Bilenko 2005). It is fundamental to prove whether the targeted region of the sunspot atmosphere is the region of the outward flow of the solar wind.

In this paper we trace the CH vs. AR analogy in the isolated sunspot during two solar rotations (active regions AR 11289 and AR 11312). There is a long-lasting depletion in the coronal and chromospheric emissions in some part of the atmosphere of this isolated sunspot. The "dark coronal corridor", seen not only in soft X-ray but in the UV as well, correlates with low intensity at 34 GHz maps and low radio brightness in o-mode at 17 GHz maps taken with the Nobeyama Radio Heliograph (NoRH). It is known that the 17 GHz brightness of a large-scale coronal hole exceeds the brightness of the quiet Sun (Gopalswamy et al. 1998). As shown by Maksimov & Prosovetsky (2002), the due regard should be paid to the coronal plasma density in CH to predict the above-mentioned contrast. Here we argue that the region of the depletion in coronal emission is the region of low plasma density in the atmosphere of the isolated sunspot of the ARs 11289 and 11312.

2. OBSERVATIONS AND ANALYSIS

The Stokes I and V maps at 17 GHz are recalculated to the right circular polarization RCP = I + V and the left circular polarization LCP = I - V maps. Assuming the predominance of x-mode emission from the source associated with the sunspot of the negative magnetic polarity S, the radio brightness in normal modes should correspond to T_o^b = RCP and T_x^b = LCP. We adopt $T_{QS} = 10^4$ K as the quiet-Sun brightness temperature according to the map restoration procedure of Koshiishi (2003).

Figure 1 presents the RCP and LCP contours of radio brightness at 17 GHz (NoRH) overlaid on some images of the coronal and chromospheric emissions. The dotted lines of the RCP contours mark the depletion in o-mode brightness beneath the level of the queit Sun of 10^4 K. A similar o-mode depletion at short cm wavelengths was reported by White et al. (1991), Grebinskij et al. (1998) and Bezrukov et al. (2011) for the case of a large isolated sunspot. As a rule, the depletion in o-mode brightness T_o^b at 17 GHz becomes observable in a longitudinal interval $|\theta| < 10° - 50°$ and turns to be deeper, up to (3–4) $\times 10^3$ K beneath the 10^4 K level or, if we add the quiet Sun level to the depletion, it is up to 6000–7000 K at the central solar meridian (CSM). The patches or some extended areas of the low absorption in the He I chromospheric line (the bright areas in Figures 1d, 2d) accompany the microwave depletion in o-mode. The lowered brightness in the coronal soft X-ray and EUV brightness overlap the 17 GHz o-mode depletion. Such a "dark coronal corridor" is clearly seen while the AR crosses the CSM.

One of the reasons for the radio brightness reduction in o-mode is the lower opacity in the case the free-free emission prevails over the gyro resonance emission

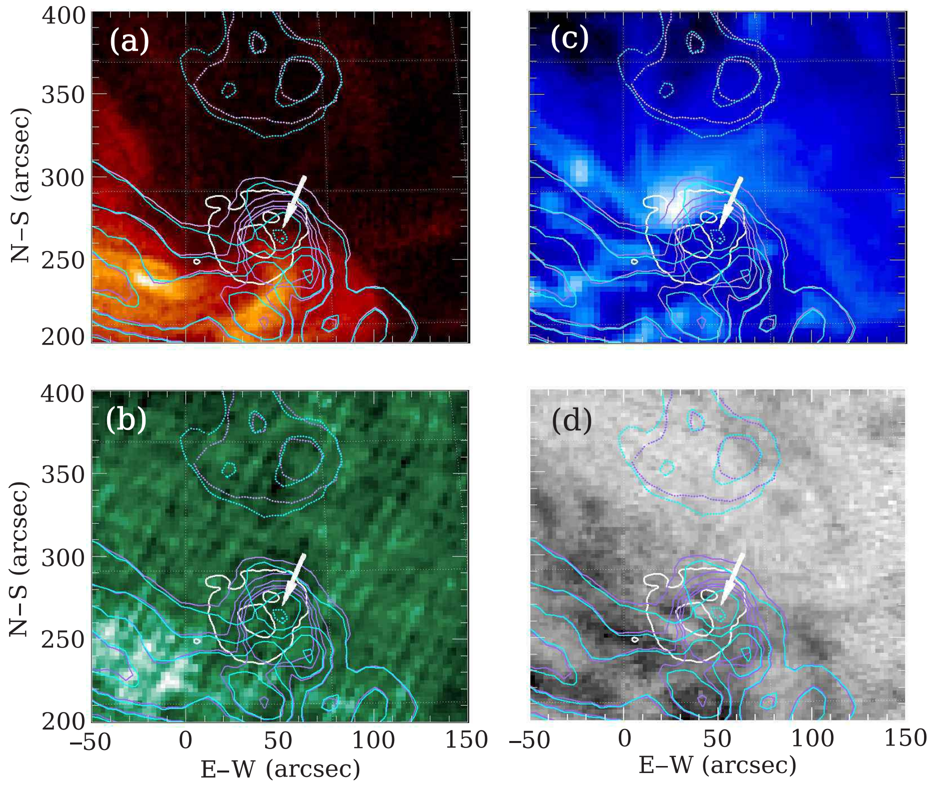

Fig. 1. AR 11289 on September 13. The contours of the 17 GHz radio brightness in LCP (violet color) and RCP (azure color) at the levels (5, 10, 15, 20) $\times 10^3$ K and (15, 20, 25, 30, 35, 40) $\times 10^3$ K respectively, and the dotted line at (8.5, 9.5, 1.05) $\times 10^3$ K observed at 03:50 UT are overlaid on: (a) the soft X-ray image taken with the XRT onboard Solar-B at 07:04 UT, (b) the NoRH image of the 34 GHz intensity taken at 02:44 UT, (c) EUV 1.74×10^{-8} m image taken with the SWAP with Al filter onboard the PROBA2 at 02:43 UT, and (d) the image in the chromospheric absorption line He I 1.083 μm taken with the CHIP at the Mauna Loa Solar observatory at 18:45 UT Note the faint emission in both coronal (a, c) and chromospheric (b, d) levels of the atmosphere above the northern part of the sunspot. Contours of the sunspot umbra and penumbra are marked by the white lines.

in strong magnetic field of a large sunspot (Grebinskij et al. 1998). The next one is the low plasma density along the ray path to the dark patch (White et al. 1991; Bezrukov et al. 2011). To simulate the radio brightness value of 6000 K one should decrease the electron density to make the ray path transparent at 17 GHz down to the height of the temperature minimum in the chromosphere. Nindos et al. (2000) reported the value of the emission measure averaged over a set of large isolated sunspots, 26.6–27.0 cm^{-5}, which results in the plasma density $\sim 5 \times 10^8$ cm^{-3} with the adopted ray path 1.9×10^9 cm.

We estimated the required decrease of the plasma density in the region of the o-mode depletion on the basis of the sunspot atmosphere introduced by Obridko & Staude (1988). To simulate the minimum brightness in o-mode $T_o^b = 6.1 \times 10^3$ K

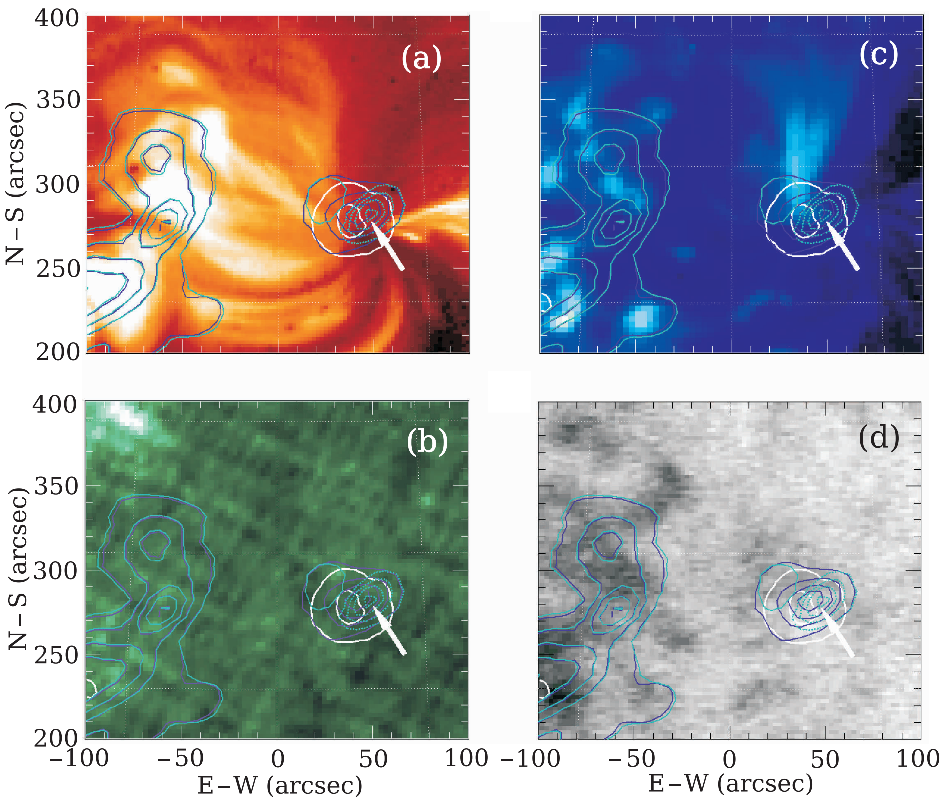

Fig. 2. AR 11312 on October 11. Contours of the 17 GHz radio brightness taken with the NoRH in LCP (violet color) and RCP (azure color) at the levels (12, 15, 18, 21, 24) $\times 10^3$ K and the dotted line at 6.5, 7.5, 8.5, 9.5) $\times 10^3$ K levels at 01:00 UT are overlaid on: (a) the soft X-ray image taken with the XRT onboard Solar-B at 06:29 UT, (b) the NoRH image of the 34 GHz intensity taken at 02:44 UT, (c) EUV 1.74 10^{-8} m image taken with the help of the SWAP with Al filter onboard the PROBA2 at 00:59 UT, and (d) the image in the chromospheric absorption line He I 1.083 μm taken with the CHIP on the Mauna Loa Solar Observatory at 01:00 UT. Note the faint emission in both coronal (a, c) and chromospheric (b, d) levels of the atmosphere above the northern part of the sunspot. Contours of the sunspot umbra and penumbra are marked by the white lines.

(Figure 4c) by the free-free radiation, the initial plasma density should be reduced 4 times with result of $N = 5\times10^8$ cm^{-3} in the depletion area at the height of the chromosphere – corona transition region. A similar estimate is reported by Bezrukov et al. (2011) for the large isolated sunspot of the AR 10325.

We note two more observational features: (1) the maximum degree of circular polarization at 17 GHz is located near the dark patch when the sunspot is near the CSM (2011 September 13 and October 11); (2) the depletion in the o-mode is observable in the longitude and time intervals symmetrical with respect to the time close to the CSM passage.

The above features are supposed to originate from the free-free radiation for the o-mode emission at 17 GHz in the magnetic fields with small tilt angle to the

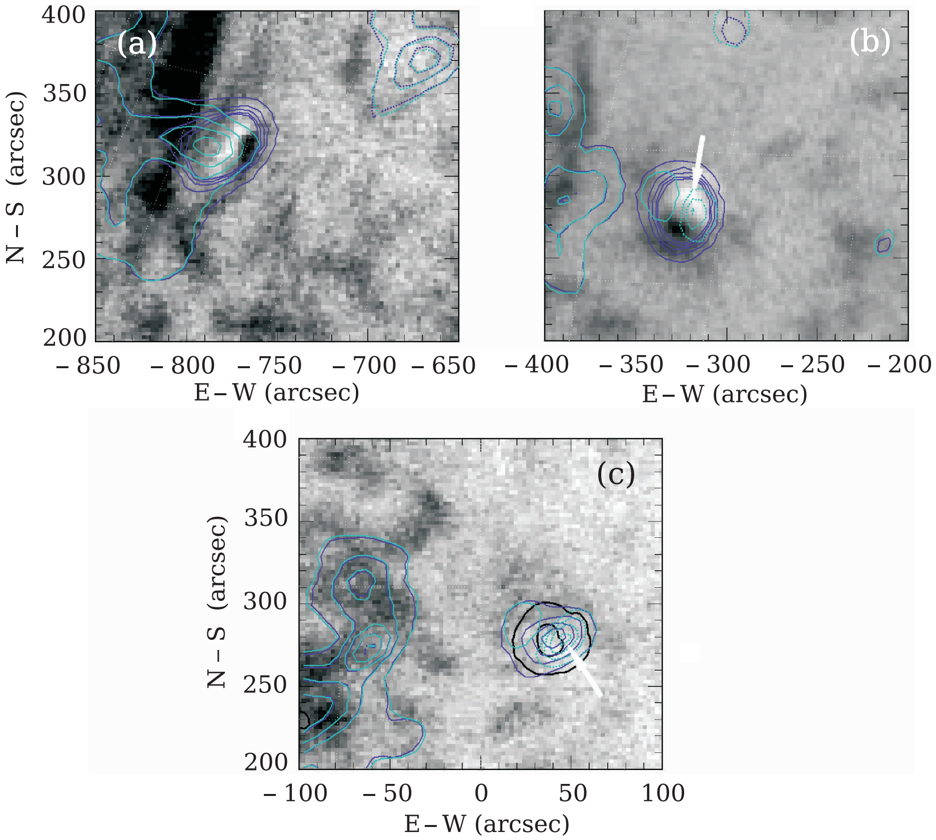

Fig. 3. AR 11312. The image in the chromospheric absorption line He I 1.083 μm taken with the CHIP at the Mauna Loa Solar Observatory on (a) October 6 at 01:20 UT and (b) October 9 at 02:10 UT. The contours of the 17 GHz radio brightness taken with the NoRH at 03:50 UT in LCP (violet color) and RCP (azure color) at the levels (12, 15, 18, 21, 24) $\times 10^3$ K and (12, 15, 18, 21)$\times 10^3$ K, respectively. The dotted line marks radio brightness of (6.5, 7.5, 8.5, 9.5) $\times 10^3$ K levels.

vertical in the dark patch and from the gyro resonance radiation from the 3rd gyro level for the x-mode at 17 GHz in nearby area of strong magnetic field. The opacity in the area of the free-free radiation depends on propagation angle α:

$$\tau^{x,o} = \frac{\xi \cdot N^2 \cdot \Delta L}{T^{3/2}\,(\nu \mp \nu_B \cdot |\cos\ \alpha|)^2}, \qquad (1)$$

where ν is the operational frequency, ν_B is the electron gyro frequency, N is the plasma density, T is the temperature, ΔL is the ray path, and ξ is taken to be constant. The optical depth in o-mode decreases at $\alpha \approx 0°$.

3. DIRECTIVITY AT 17 GHz

Let us analyze the directivity of 17 GHz emission, i.e., the radio brightness $T_x^b(\theta)$, $T_o^b(\theta)$, and the degree of circular polarization $P(\theta)$ as a function of heliolongitude θ. The degree of circular polarization P reads:

$$P = \frac{T_x^b(\theta) - T_o^b(\theta)}{T_x^b(\theta) + T_o^b(\theta)}. \tag{2}$$

In the case of the free-free radiation in a weak magnetic field ($\nu_B \ll \nu$) and in the optically thin region ($\tau^x \ll 1, \tau^o \ll 1$) the equations (1) and (2) transform to:

$$P = n\frac{\nu_B}{\nu} \cos\,\alpha\ , \tag{3}$$

where n is the spectral index (for details see Gelfreikh & Shibasaki 1999). In the case of $\alpha \ll 1$, the optical depth of the gyro level s ($s \geq 2$) can be approximated as follows (Zheleznyakov 1970): $\tau^x \sim \sin^{2s-2}\,\alpha\,(1 + |\cos\,\alpha|)^2$ and $\tau^o \sim \sin^{2s-2}\,\alpha$ $(1 - |\cos\,\alpha|)^2$, valid for $s \geq 2$. According to equation (2), the optically thin gyro level s provides the degree of circular polarization $P\,(\alpha)$:

$$P \propto \frac{4\,\cos\,\alpha}{3 + \cos\,2\alpha}. \tag{4}$$

The curve $P\,(\alpha)$ (4) looks like "overextended cosine" for the source of gyro resonance radiation from an optically thin gyro level. On the contrary, if the source of the gyro resonance radiation from the optically thick gyro level is wider than its thickness, the directivity $P\,(\theta)$ should resemble the cosine, especially at longer wavelengths of 4–6 cm near the solar limb (Lubyshev 1977).

The observed directivity of the degree of circular polarization $P\,(\theta)$ (Figure 4b) at the point of current maximum brightness of $T_x^b(\theta)$ is more like an "overextended cosine" than a cosine. We conclude that the bulk of x-mode emission at 17 GHz comes from the semi-transparent 3rd gyro resonance level over the sunspot-associated source.

In the area of o-mode depletion T_o^b preserves its low brightness, i.e., (1–3)$\times 10^3$ K beneath the quiet Sun level of 10^4 K (Figure 4c). According to our simulations with the help of the adopted sunspot atmosphere (Obridko & Staude 1988), the observed directivity of T_o^b corresponds to the directivity of the free-free radiation in the strong magnetic fields of the sunspot. Near the solar limb, $\theta = 60°$, the brightness drops to $T_x^b \approx \mathrm{T}_o^b \approx 10^4$ K and the polarization P drops abruptly as well (Figure 4d).

4. DISCUSSION AND CONCLUSIONS

It is confirmed that the microwave source associated with a large isolated sunspot shows a low radio brightness in the o-mode at the wavelengths as short as 1.76 cm. While the radio brightness in the x-mode is about 10 times brighter than the quiet Sun, the brightness in the o-mode can be ~ 1.5 times fainter. This low radio brightness at short centimeter wavelengths is traced to the low plasma density in the region of the sunspot atmosphere, which appears to be dark in the soft X-ray emission (dark patch) and becomes brighter in the chromospheric He I

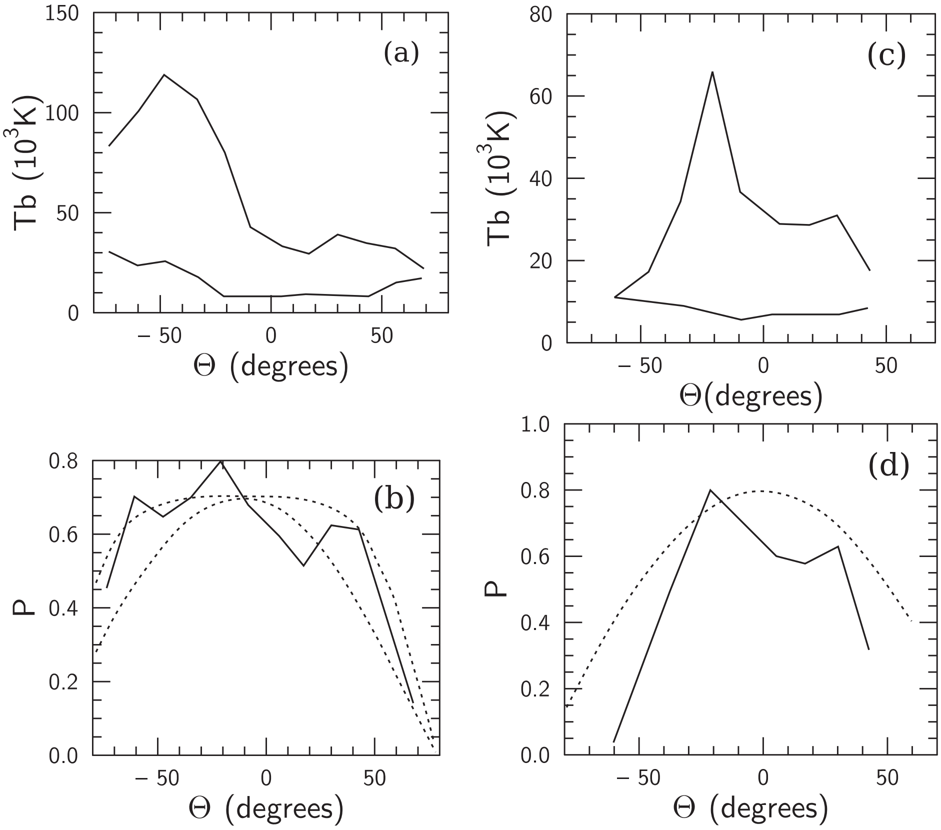

Fig. 4. AR 11312. The longitudinal dependence of (a) the 17 GHz radio brightness in both RCP ($T_o^b(\theta)$) and LCP ($T_x^b(\theta)$) and (b) the degree $P(\theta)$ of circular polarization at the point of the current maximum brightness in LCP. The longitudinal dependence of (c) the radio brightness in both RCP and LCP and (d) the degree of circular polarization at the point of the current minimum brightness in RCP. The dashed curves show the cosine and the "overextended cosine" (4).

absorption line. All these features are characteristic of a coronal hole as well. It is worth proving whether the targeted region of the sunspot atmosphere is the region of the open magnetic field lines and the outward plasma flow of the solar wind.

The depletion appears in o-mode emission within the 17 GHz source associated with the large isolated sunspot AR 11289 and with the AR 11312 during its decay phase in the next solar rotation. On the basis of model simulation of the free-free radiation, which is proved to be the only source of the o-mode emission in the dark patch, we estimated the plasma density as low as 5×10^8 cm^{-3} in the region of the depletion.

The x-mode emission of the 17 GHz sunspot-associated source is regarded as the gyro resonance emission from the 3rd semi-transparent gyro level. The above radiation mechanism is proven by comparison of the observed directivity of circular polarization $P(\theta)$ with $P(\alpha)$ in the form of an "overextended cosine" for a semi-transparent gyro level. We believe that the above similarity proves the near radial structure of the magnetic field in corresponding areas of the sunspot atmosphere as well.

It is worth noting some indications of predominantly anti-phase variations of T_x^b and T_o^b (Figure 4c) in the current point of the minimum T_o^b. If proven to be significant, the radio brightness variations can reveal the variations of the magnetic field or temperature in the dark patch. The preliminary inspection of the Doppler Fe XII (1.9512×10^{-8} m) velocity map of the AR 11289 taken with the EIS onboard Solar-B on September 13 shows the blue-shifted velocities up to –12 km/s within the region of the coronal depletion. To evaluate the plasma flow precisely, further analysis of the EUV observations is required.

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