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Plasma distribution of Comet ISON (C/2012 S1) observed using the radio scintillation method

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ABSTRACT

We report the electron density in a plasma tail of Comet ISON (C/2012 S1) derived from interplanetary scintillation (IPS) observations during November 1–28, 2013. Comet ISON showed a well-developed plasma tail (longer than 2.98×10^7 km) before its perihelion passage on November 28. We identified a radio source whose line-of-sight approached the ISON's plasma tail in the above period and obtained its IPS data using the Solar Wind Imaging Facility at 327 MHz. We used the *Heliospheric Imager* onboard the *Solar-Terrestrial Relation Observatory* to distinguish between the cometary tail and solar eruption origins of their enhanced scintillation. From our examinations, we confirmed three IPS enhancements of a radio source 1148–00 on November 13, 16, and 17, which could be attributed to the disturbance in the cometary tail. Power spectra of 1148–00 had the steeper slope than normal ones during its occultation by the plasma tail. We estimated the electron density in the ISON's plasma tail and found 84 cm^{-3} around the tail axis at a distance of 3.74×10^7 km from the cometary nucleus and an unexpected variation of the electron density in the vicinity of the tail boundary.

1. Introduction

Comet ISON (C/2012 S1) was found out by Nevski and Novichonok using a 0.4 m telescope of the International Scientific Optical Network on September 21, 2012 (Nevski et al., 2012). Because it was one of the sun-grazing comets, which had a perihelion distance of 0.0125 astronomical units (AU) (1.87×10^6 km), Comet ISON was expected to emit a large amount of gas and then become extremely bright before and after its perihelion passage. However, the ISON's nucleus collapsed on November 28, 2013 when it passed the closest point to the Sun on its orbit (Knight and Battams, 2014; Lisse and CIOC Team, 2014), and so far no one has confirmed any on-orbit fragments after the time when Comet ISON's remnants went out of the space-borne coronagraph field-of-view (e.g. http://hubblesite.org/hubble_discoveries/comet_ison). During pre-perihelion, Comet ISON showed a well-developed plasma tail. The measurement of plasma, particularly its electron density, usually requires an in situ observation by a comet probe. Direct plasma measurements have been carried out in the downstream of the cometary nucleus for Comets Giacobini-Zinner (Meyer-Vernet et al., 1986), Hyakutake (Gloeckler et al., 2000), and McNaught (Neugebauer et al., 2007). However, there was no spacecraft to measure the plasma tail of Comet ISON directly.

Remote sensing of the cometary plasma tail using radio observations was begun in the 1950s (Whitfield and Högbom, 1957). Wright and Nelson (1979) observed some radio source occultation by plasma tails of Comets Kohoutek and West and found peak electron densities of approximately 2–5 $\times 10^4$ cm^{-3} in their tails from observed anomalies of radio source positions. The interplanetary scintillation (IPS) is a phenomenon in which radio signals from distant radio sources fluctuate by density irregularities of the solar wind, and it is well known that interplanetary disturbances such as coronal mass ejections (CMEs) cause an abrupt increase in IPS (Hewish et al., 1964; Gapper et al., 1982). A cometary plasma tail may also be a potential cause for the IPS enhancement. Ananthakrishnan et al. (1975) observed an IPS of a radio source at 327 MHz during its occultation by a plasma tail of Comet Kohoutek. From their result, Lee (1976) estimated the root-mean-square fluctuation of the electron density as $\approx$80 cm^{-3}. After their pioneering work, similar observations have been made for Comets Halley (Alurkar et al., 1986; Ananthakrishnan et al., 1987; Slee et al., 1987), Wilson (Slee et al., 1990), Austin (Janardhan et al., 1991), Hale-Bopp (Abe et al., 1997), and Schwassmann-Wachmann 3-B (Roy et al., 2007). In spite of these studies since 1975, the IPS

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enhancement due to the cometary tail is still controversial. Alurkar et al. (1986) and Slee et al. (1987) presented positive results, while Ananthakrishnan et al. (1987) reported that no significant enhancement of scintillation was observed for a radio source occultation of Comet Halley. Because the IPS observation alone could not distinguish between the cometary tail and solar-wind irregularity origins of the enhanced scintillation, it was difficult to obtain a conclusive result for the IPS of the plasma tail.

In the current study, we examine the IPS enhancement due to the plasma tail of Comet ISON using the radio telescope system of the Solar-Terrestrial Environment Laboratory (STEL), Nagoya University during November 1–28, 2013. To improve limitations of the IPS observation mentioned above, we analyze data of an imaging instrument onboard the *Solar-Terrestrial Relation Observatory* (STEREO) spacecraft (Kaiser et al., 2008). From these examinations, we estimate the electron density in the plasma tail of Comet ISON. The outline of this article is as follows: Section 2 describes IPS observations, images taken by STEREO and amateur astronomers, and a method for event identification. Section 3 provides analyses of IPS enhancement events by the ISON's tail. Section 4 discusses the results and gives the main conclusion of our study.

2. Data and method

2.1. Data

STEL IPS observations at 327 MHz have been carried out regularly using ground-based radio telescopes to investigate the solar wind and interplanetary disturbance since the early 1980s (Kojima and Kakinuma, 1990). The Solar Wind Imaging Facility (SWIFT) has been in operation since 2010 and capable of observing ≈40 radio sources in a day (Tokumaru et al., 2011). For each radio source, the solar-wind disturbance factor, the so called "*g*-value" (Gapper et al., 1982), is derived from an IPS observation. In this study, we use the *g*-value data obtained using SWIFT. A *g*-value represents the relative level of density fluctuation integrated along a line-of-sight from a radio source to a radio telescope, and is defined by the following equation (Tokumaru et al., 2003, 2006; Iju et al., 2013):

$$g^2 = \frac{\int_0^\infty dz \{\Delta N_e(\varepsilon, \psi, r)\}^2 \omega(z)}{\int_0^\infty dz \{\Delta N_{e0}(\varepsilon, \psi, r)\}^2 \omega(z)}, \tag{1}$$

where z is the distance along a line-of-sight, ε and ψ are the heliographic longitude and latitude, respectively, r is the radial distance from the Sun, $\Delta N_e(\varepsilon, \psi, r)$ is the observed fluctuation level of plasma (electron) density, $\Delta N_{e0}(\varepsilon, \psi, r)$ is the yearly mean of $\Delta N_e(\varepsilon, \psi, r)$, and $\omega(z)$ is the IPS weighting function (Young, 1971) in a weak scattering condition. The $\omega(z)$ is given by the following formula (Tokumaru et al., 2003):

$$\omega(z) = \int_0^\infty dk k^{1-q} \sin^2\left(\frac{k^2 z \lambda}{4\pi}\right) \exp\left(-\frac{k^2 z^2 \Theta^2}{2}\right), \tag{2}$$

where k, q, λ, and Θ are the spatial wavenumber of density fluctuations, the spectral index of the density turbulence, the apparent angular size of a radio source, and the wavelength for observing frequency, respectively. We use Eq. (2) with $q = 11/3, \lambda = 0.92$ m, and $\Theta = 0.1''$ for STEL IPS observations. The $\Delta N_e(\varepsilon, \psi, r)$ and $\Delta N_{e0}(\varepsilon, \psi, r)$ are assumed to be proportional to the electron density $[N_e(\varepsilon, \psi, r)]$ and its yearly mean $[N_{e0}(\varepsilon, \psi, r)]$, respectively (Coles et al., 1978). Ananthakrishnan et al. (1980) reported that the relationship between $\Delta N_e(\varepsilon, \psi, r)$ and $N_e(\varepsilon, \psi, r)$ varied with the velocity gradient of the solar wind. According to Asai et al. (1998), however, the relative fluctuation level remained unity within a standard deviation in a velocity range of 400–600 km s^{-1} and were dominated mainly by the density rather than the velocity of the solar wind for the 327 MHz IPS observation. Therefore, the above assumptions are valid for applying to Eq. (1), and we obtain:

$$g^2 \propto \frac{\int_0^\infty dz \{N_e(\varepsilon, \psi, r)\}^2 \omega(z)}{\int_0^\infty dz \{N_{e0}(\varepsilon, \psi, r)\}^2 \omega(z)}. \tag{3}$$

Because of a normalized index by a mean, the *g*-value is around unity for a quiet condition of the solar wind. The *g*-value becomes greater than unity with dense plasma or high turbulence on a line-of-sight, but lesser than unity for a rarefaction of the solar wind.

The IPS observation alone cannot distinguish between the cometary plasma tail and CMEs origins of an enhanced *g*-value. To confirm CMEs, we use images taken by the *Heliospheric Imager* (HI; Eyles et al., 2009) onboard the STEREO-A spacecraft. HI comprises the HI-1 and HI-2 cameras, which take images of the interplanetary space between 4° and 24° (elongation from the Sun's center) with a cadence of 40 min and between 18.7° and 88.7° with a cadence of two hours, respectively. We use their level-2 data processed with a running window of 11 days and differential images, which are available on the STEREO Science Center web site (http://stereo-ssc.nascom.nasa.gov).

2.2. Event identification and analysis

We measured the outspread angle and the length of the ISON's plasma tail from photographs taken by two amateur astronomers. On November 17, 2013, a narrow-field (1.87° × 2.89°) image was taken by G. Rhemann in Namibia (available at www.astrostudio.at/all.php), while a wide-field (8.71° × 5.76°) image was obtained by M. Jäger in Austria (available at http://cometpieces-at.webnode.at). Table 1 presents the outspread angle $[\theta_{tail}]$ and length $[L_{tail}]$ of the ISON's plasma tail derived from these images. These measurements and an ephemeris were used to identify radio sources occulted by the plasma tail.

We obtained *g*-values of ≈40 radio sources and made a map of them in the sky plane, the so-called "*g*-map" (Gapper et al., 1982), for each day during November 1–28, 2013. A location of Comet ISON with an outline of the plasma tail was examined with respect to radio sources on a *g*-map for each day. From this examination, we found that the radio source 1148–00 (R.A. = 11^{h}50^{m}46^s, Dec. = –00°24′13″ in the J2000.0 coordinates) was occulted by the ISON's tail during the 12–18th. We assumed that a *g*-value of 1.5 or more indicates a disturbance of plasma (Iju et al., 2013), and identified then five candidates for the IPS enhancement by the cometary tail. These scintillation enhancements were observed on 1148–00 between the 13th at 23:09 and the 17th at 22:53 UT; we gained a *g*-value = 1.375 on the same source at 23:13 UT on the 12th. On the other hand, we identified other sources without the occultation as controls. Table 2 summarizes an ephemeris of Comet ISON with the plasma tail from November 14 until 18. Fig. 1 shows a daily change of Comet ISON's position with respect to radio sources including 1148–00 in the same period. From these observations, we estimated the number density of electrons in the plasma tail. For each IPS enhancement event, we calculated the intersection point $[z_a]$ of the cometary tail axis and the projected line-of-sight on a tail-axial surface, the distance $[d_c]$ between the

Table 1
Outspread angles and lengths of Comet ISON's plasma tail on November 17, 2013.

	θ_{tail} (°)	L_{tail} ($\times 10^7$ km)
Minimum	4.6 (dense region)	2.98
Maximum	8.9 (sparse region)	4.47