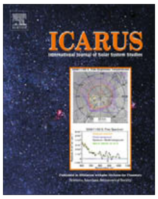
Icarus 204 (2009) 589–596

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus



Short-term variability of Jupiter's extended sodium nebula

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ARTICLE INFO

Article history:
Received 20 February 2008
Revised 17 June 2009
Accepted 6 July 2009
Available online 29 July 2009

Keywords:
Io
Jupiter
Volcanism
Jupiter, Magnetosphere
Jupiter, Satellites

ABSTRACT

Ground-based optical observations of D_1 and D_2 line emissions from Jupiter's sodium nebula, which extend over several hundreds of jovian radii, were carried out at Mt. Haleakala, Maui, Hawaii using a wide field filter imager from May 19 to June 21, 2007. During this observation, the east–west asymmetry of the nebula with respect to the Io's orbital motion was clearly identified. Particularly, the $D_1 + D_2$ brightness on the western side of Jupiter is strongly controlled by the Io phase angle. The following scenario was developed to explain this phenomenon as follows: First, more ionospheric ions like NaX^+, which are thought to produce fast neutral sodium atoms due to a dissociative recombination process, are expected to exist in Io's dayside hemisphere rather than in the nightside one. Second, it is expected that more NaX^+ ionospheric ions are picked up by the jovian co-rotating magnetic field when Io's leading hemisphere is illuminated by the Sun. Third, the sodium atom ejection rate varies with respect to Io's orbital position as a result of the first two points. Model simulations were performed using this scenario. The model results were consistent with the observation results, suggesting that Io's ionosphere is expected to be controlled by solar radiation just like Earth.

1. Introduction

1.1. Io as a major plasma source of Jupiter's magnetosphere

Several spacecraft that have had encounters with Jupiter have revealed complicated relations among the Io's volcanism, atmospheric, and plasma environments in Jupiter's magnetosphere. Voyager and other follow-on spacecrafts have obtained images of Io's volcanic eruptions which reach as high as a few hundred kilometers above its surface. In situ observations by Voyager showed that heavy sulfur and oxygen ions which originate from Io's volcanoes, dominate the plasma in Jupiter's inner magnetosphere. The ions in Io's ionosphere are picked up by Jupiter's co-rotating magnetic fields and form the so-called Io plasma torus. Ions in the Io plasma torus have emission lines in a wide range of wavelengths due to collisional excitation with ambient electrons. The [SII] emissions at 671.6 nm and 673.1 nm are visible from the ground, and are important targets of ground-based observations.

1.2. Neutral atoms from Io

While ions and electrons are strongly controlled by Jupiter's magnetic field, the motion of neutral particles is affected only by the gravitational field. Sodium atoms play an important role as tracers of neutral clouds. Although sodium is one of the minor components in Io's volcanic species, its large photon scattering cross-section for the solar light at the D_1 and D_2 lines makes its observations from the ground much easier. A nebula consisting of neutral sodium atoms, which extends far beyond Jupiter's magnetosphere and also its gravitational-sphere, was captured for the first time by Mendillo et al. (1990). This suggests that sodium atoms are sufficiently accelerated to escape from Jupiter's gravitational-sphere.

Wilson and Schneider (1994) and Wilson et al. (2002) showed that pick-up of NaX^+ ions from Io's ionosphere by Jupiter's magnetic field followed by their subsequent destruction in the Io plasma torus is considered a dominant process for producing high-speed sodium atoms. A structure called "stream" is formed by this process. Although the atmospheric sputtering of sodium atoms is also an efficient loss process in Io's atmosphere, it cannot provide sufficient enough velocity to sodium atoms to escaping from Jupiter's gravitational-sphere. A small feature called "jet" is a result from a similar process as "stream", but the destruction of NaX^+ occurs in Io's ionosphere. Therefore, the lifetime of NaX^+ is much shorter than that in the Io plasma torus. This short lifetime results in a small directional feature in the anti-Jupiter direction (Wilson and Schneider, 1999).

Mendillo et al. (2004) revealed that the annual change in size and brightness of the sodium nebula correlates with the infrared brightness of Io. Since the infrared brightness of Io is thought to correspond to the volcanic activity on Io, this suggests that the

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0019-1035/$ - see front matter © 2009 Elsevier Inc. All rights reserved.
doi:10.1016/j.icarus.2009.07.023

abundance of magnetospheric particles is controlled by Io's volcanic activity. It can be said that sodium is not only a tracer for neutral clouds, but also an index for Io's volcanic activity.

1.3. Daily variation of sodium nebula

Flynn et al. (1994) suggested that the short-term variation of the nebula is caused by Io's orbital motion, not by volcanic change. Particularly, the eastern side of the sodium nebula is more strongly controlled by Io's orbital motion than the western side. However, they did not show any mechanism that causes the differences in the sodium nebula between the eastern and western sides.

We made new observations to monitor the sodium nebula and the Io plasma torus from May through June 2007. Our observation results showed unexpected aspects of the sodium nebula that are different from those seen by Flynn et al. (1994).

2. Observations

2.1. Observation of sodium nebula

Our observation was carried out at Mt. Haleakala, Maui, Hawaii from May 19 through June 21, 2007. The optical instrument used for this observation consisted of a small refractor (10-cm aperture), an interference filter for the Na D-line (center wavelength of 589.5 nm with a FWHM of 1.7 nm), a linear shape occulting ND filter to mask the bright image of Jupiter, and a CCD camera. In addition, a Na-off filter (620.0 nm ± 5 nm) was used to discriminate the scattered light. The full field of view (FOV) of the optics is 2.5° ($\sim 400R_J$). Actually, the entire size of the nebula is $\sim 1000R_J$ (Mendillo et al., 1990). However, the outer region of the nebula is not expected to clearly show such a short-term periodic variation. Therefore, our optical system is optimized for imaging the inner region of the nebula (5–$150R_J$ from Jupiter). Jupiter's opposition in 2007 was on June 6, which falls in middle of the observation period. Therefore, the Io phase angle from Earth is approximately equal to that from the Sun. The Io phase angle does not represent only that from Earth, but also that from the Sun in this study.

The Na-off images must be multiplied by a certain factor to subtract the scattered light from the Na-on images correctly. This factor can be estimated from the count rates of the stars that appear on both the Na-on and Na-off images if their spectral types are known. Usually, there was not any spectral standard star in the field of view. However, photon fluxes of stars in the field of view at each wavelength can be inferred from their spectral type and magnitude, if they are not variable stars. A relationship,

$$f_a^\lambda = 2.51^{(m_b - m_a)} f_b^\lambda, \tag{1}$$

where f_a^λ and f_b^λ are the photon fluxes of star "*a*" and "*b*" at a wavelength of λ, m_a and m_b are the magnitudes of star "*a*" and "*b*" at the same spectral band, respectively, and does form between the same spectral type stars. Spectral types and magnitudes of the stars for data reduction in the field of view were obtained from the SIMBAD Astronomical Database. On the other hand, Burnashev (1985) provided the photon flux at each wavelength, magnitude, and spectral type of each standard star. Applying the relationship described above between stars in the field of view and the stars listed stars by Burnashev (1985) whose spectral type is the same to the star in the field of view, we can estimate photon fluxes of the stars in the field of view at the wavelengths of Na-on and Na-off. In this case, star "*a*" is chosen from the field of view, and "*b*" has the same spectral type as "*a*" listed by Burnashev (1985). The factor, by which the Na-off image must be multiplied, is described as,

$$\alpha = \frac{f_{\text{Na-on}} C_{\text{Na-off}}}{f_{\text{Na-off}} C_{\text{Na-on}}}, \tag{2}$$

where α is the factor, $f_{\text{Na-on}}$ and $f_{\text{Na-off}}$ are photon fluxes of the star at wavelengths of Na-on and Na-off, respectively, and $C_{\text{Na-on}}$ and $C_{\text{Na-off}}$ are the total count rates of the star at wavelengths of Na-on and Na-off, respectively. After subtracting the scattered light, a conversion factor to calculate the absolute brightness from the count rates, which is described as *Rayleighs*/*counts*, must be obtained. Not only α, but also a conversion factor from the count rates to a Rayleigh unit can be calculated from the photon fluxes of the stars. Both α and the factor for the calibration of absolute intensity are averaged values of those obtained by using several stars in the field of view and those listed as standard stars to achieve a high accuracy. The standard deviations of these two values, obtained by using several stars in this data reduction, are taken into account to define the error bars in the resulting observation data. The brightness of the terrestrial sodium airglow was measured at $200R_J$ from Jupiter on the northern or southern sides of the planet to subtract it from the sodium D-line images. Even after removal of scattered light from the Na-on image, some star images still remained. Most of these images were removed by using a median filter. The errors due to dark noise counts and fluctuation of photons were also taken into account and are represented in the results as error bars.

2.2. Observation of Io plasma torus [SII] emission

Observations of the 671.6- and 673.1-nm [SII] emissions in the Io plasma torus were also made by Kagitani (2007) at the Haleakala observatory, Maui, using a high-dispersion Echelle spectrograph coupled to a 40-cm Schmidt-Cassegrain telescope for the same period of time as the sodium nebula observation. The spectrograph slit has a sufficiently wide enough FOV to cover the plasma torus in the east–west direction. The slit was aligned to the centrifugal equator on which the plasma torus is aligned.

3. Observation results

3.1. Daily variation as a general trend

In the first half of the observation period (May 19–June 3), the sodium nebula showed a distinct enhancement as seen in Fig. 1. The change of the sodium nebula can be clearly seen in the images shown in Fig. 2. This enhancement was probably caused by a volcanic burst on Io because the [SII] emissions also showed an enhancement during the same period (Fig. 3). The growth phase of the [SII] emissions was not identified because the beginning of the observation of the [SII] emissions was delayed from the commencement of the sodium nebula observation by 8 days. However, it is obvious that the brightness of the [SII] emissions and that of the sodium nebula were decreasing in a similar way. Brown and Bouchez (1997) monitored the sodium clouds and the [SII] emission of the Io plasma torus. They showed that the decrease in brightness of the sodium clouds was followed by that of the [SII] emission with a time lag of several tens days in contrast to our results. There is no reasonable interpretation for what controls the time lag of the brightness between the [SII] and sodium emissions. In the latter half of our observation period (after June 8), the brightnesses of both the sodium nebula and the [SII] emissions were faint and stable (Figs. 1 and 3). We assume that the latter half of the period was quiet not only volcanically, but also magnetospherically. This period (after June 8) is suitable to identify the variation in the sodium nebula with respect to the Io phase angle. Only this stable period will be further discussed in this study.