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Note

The effect of solar flares, coronal mass ejections, and solar wind streams on Venus' 5577 Å oxygen green line

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ABSTRACT

We observed the Venusian 5577.3 Å OI (^1S–^1D) (oxygen green line) nightglow emission feature after solar flares, coronal mass ejections (CMEs), and solar wind streams from December 2010 to July 2012 using the high resolution Astrophysical Research Consortium Echelle Spectrograph on the Apache Point Observatory 3.5 m telescope. For the first time since 2004, we detected the green line. The emission is highly temporally variable, with the strongest emission detected being comparable to the previously known brightest detection, and to occur after each of the three types of solar events. We find the greatest emission occurs after CMEs and suggest that particle precipitation is the main contributor to green line emission.

1. Introduction

Earth, Venus, and Mars all formed close to the Sun under similar conditions and from roughly the same materials. Despite having common origins of formation, they currently have different atmospheres due to the evolutionary pathways taken by each planet, resulting in two CO_2-dominated atmospheres (those of Mars and Venus) and one N_2/O_2-dominated atmosphere (that of Earth). In order to understand the processes that led to the evolution of these atmospheres we study the present-day atmospheric chemistry. Furthermore, understanding of chemical reactions within the upper atmosphere of a planet can be used to trace dynamical processes such as winds and transport mechanisms. We infer the properties of these chemical reactions by observing nightglow: emission in the upper atmosphere from atoms and molecules on the night side of a planet. Here we consider three such processes: photodissociation/transport, dissociative recombination, and radiative recombination (Slanger and Wolven, 2002).

Photodissociation/transport is the process by which solar extreme ultraviolet (EUV) photons impact on the day side of a planet, ionizing and dissociating atoms and molecules. The products are transported to the night side where they recombine with other atoms/molecules to produce nightglow. Venus has a four-day circulation pattern where photodissociated material is transported from the subsolar SS point to the antisolar AS point in two days. Dissociative recombination and radiative recombination are two similar processes, where electrons combine with molecular ions (dissociative recombination) or atomic ions (radiative recombination), causing molecular ions to dissociate to neutral atoms and molecules, and atomic ions to become neutral. These neutral products can occupy excited states that can decay to produce nightglow. The electrons responsible for these two processes can come from various solar sources and precipitate from upper atmospheric layers down to lower atmospheric layers, a process known as electron precipitation (Fox and Kliore, 1997; Fox, 2012 and Phillips et al., 1986), with higher energy electrons penetrating to lower altitudes.

Several nightglow emission features have been detected in the spectra of Venus. For this paper, we focus exclusively on the OI^1S–^1D) line at 5577.3 Å (oxygen green line). The oxygen green line is a persistent feature in Earth's atmosphere but is highly variable in Venus' atmosphere. In 1975, the Venera 9 and 10 spacecraft searched for, but did not detect, the green line; only an upper limit of 10 R was obtained (Krasnopolsky et al., 1976). Venus' green line was first seen in 1999 by Slanger et al. (2001) with an intensity of 150 R, comparable to the terrestrial emission strength. It was subsequently observed at weaker intensities until 2004, after which it was not detected (Slanger et al., 2006) until this study.

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Slanger et al. (2012) proposed that the temporal variability of Venus' green line is due to variations in the solar cycle, where increased emission strength is directly proportional to solar activity. The Venera spacecraft observed Venus during a solar minimum, which may explain why the green line was not detected. The largest green line detection was reported by Slanger et al. (2001) in 1999, 2 years before the 2001 solar maximum. The green line emission was variable throughout solar maximum and decreased as the Sun moved into solar minimum. We suggest that the variability of the green line is due to short term solar events that occur more frequently during solar maximum. We propose three types of solar events that may be responsible for green line emission, as they produce large amounts of EUV photons and/or charged particles: solar flares, coronal mass ejections (CMEs), and dense solar wind streams (SWSs) with associated co-rotating interaction regions (CIRs). Each of these events are known to generate increased terrestrial nightglow and aurorae (Tsurutani et al., 2006; Peterson et al., 2008).

Solar flares are sudden atmospheric brightenings on the Sun (see Hudson, 2010 for a review) which produce charged particles and emit increased radiation across the electromagnetic spectrum, particularly in the X-ray, radio, EUV, and Hα. Flares are categorized on a logarithmic scale based on their 1–8 Å peak X-ray flux and are ordered, from weakest to strongest, A, B, C, M, X. Each letter corresponds to an order of magnitude, which is further broken down by numbers 1.0–9.9. The photons from a flare have an immediate effect on the day side of Venus by photodissociating molecules and ionizing atoms. However, nightglow is produced 2–3 days later, after the material is transported to the night side via the SS-AS circulation pattern.

CMEs are ejections of plasma and unbound magnetic fields above the Sun's photosphere near the corona. They are commonly associated with solar flares, especially large M- and X-class flares. CMEs typically have speeds of 500–1000 km s^{-1} and take 1–2 days to reach Venus. They are capable of injecting increased amounts of electrons into the upper atmosphere of a planet on both the day and night side. For a magnetized planet, a CME can couple to the magnetic field lines, driving plasma to day and night side. For Venus, an unmagnetized planet, Zhang et al. (2012) has shown that magnetic reconnection events produce plasmoids that deposit electrons onto the night side. While it takes 1–2 days for a CME to reach Venus, atmospheric emission is produced immediately upon impact, similar to aurorae on Earth (Phillips et al., 1986).

SWSs are either faster, lower density plasma or slower, higher density plasma compared to the average solar wind speed and density. The solar wind moves in a spiral, due to the rotation of the Sun. Where fast SWSs meet slow SWSs, a co-rotating interaction region (CIR) of increased plasma density and magnetic field strength is created (Gosling and Pizzo, 1999). The plasma density of a CIR increases with distance from the Sun and at the distance of Venus the densities are typically less than the plasma densities from CMEs. However, CIRs and their associated dense SWSs take several days to move across a planet and serve as a weaker but longer lasting source of charged particles (Tsurutani et al., 2006).

Previous observations of the green line and solar activity up to one week prior to observations are listed in the first half of Table 1. At least one major solar event occurs within one week of every detection of the green line, but there are no such events before non-detections. We chose a period of one week based on terrestrial aurorae. On Earth, the effects from CMEs can exceed a week. We do not expect such long effects on Venus as it has no intrinsic magnetic field to store plasma to continually produce aurorae. It takes 2–3 days after a flare for photodissociated material from the day side of Venus to reach the night side and it is unknown how long nightglow emission will be affected, but we assume that its effects will last longer for larger solar events.

To test our hypothesis that solar events are connected to green line emission, we observed Venus as a Target of Opportunity (ToO), allowing us to override other observing programs on short notice, in April–July 2012 shortly after M- and X-class flares and CMEs. Here, we present our results from these observations and suggest that electrons from CMEs and SWS, as well as photodissociation/transport from flares, are responsible for green line emission.

2. Observations and data reduction

We observed Venus using the Astrophysical Research Consortium (ARC) 3.5-m telescope at Apache Point Observatory (APO) and the ARC Echelle Spectrograph (ARCES). ARCES is a high resolution ($R \sim 31{,}500$) spectrograph with spectral coverage from 3200 to 10,000 Å. We used a slit size of $1.6'' \times 3.2''$, corresponding to a projected slit size of $\sim 650 \times 1300$ km to 475×950 km on Venus for our observed range of 0.41–0.55 AU. We observed Venus only when its orbital velocity was such that its spectrum was sufficiently Doppler shifted, separating the Venusian feature from the terrestrial. For ARCES, this required a Doppler shift of $\gtrsim 6$ km s^{-1}, slightly more than the dispersion of the instrument. Our observations covered a relative speed range of 11.3–13.3 km s^{-1}. In order to minimize the amount of scattered light from the Venusian day side, we restricted our observations to times when Venus was less than 50% illuminated.

By monitoring real-time solar activity of the Sun through http://www.spacew-eather.com and using space weather models provided by the Goddard WSA_Enlil Solar Wind Prediction models to track CMEs (http://www.swpc.noaa.gov/wsa-enlil/), we were notified when a large solar flare was emitted and were provided an estimate of when a CME would impact Venus. With this quick notification, we can observe as soon as 3 h after such an event occurred. We observed Venus after three separate M- and X-class flares and two CMEs between April and July 2012. The bottom half of Table 1 lists the details of these observations. Additionally, we observed Venus in December 2010 as a CIR passed over the planet.

For each solar event, we collected spectra of the Venusian night and day side and A0V flux standard stars. We scaled and subtracted our day side spectra from the night side to account for scattered day side light and reflected solar spectrum. The slit was positioned at the antisolar point and on the equatorial and polar limb to explore the spatial variability of the green line emission.

We performed standard data reduction involving flat fielding, bias subtraction, and wavelength calibration. We flux calibrated our exposures using A0V standard stars that were observed at similar airmasses as Venus and scaled the spectra by exposure time, seeing, and airmass. To account for telescope transmission (the fraction of light lost outside of the slit due to variations in atmospheric seeing), we adopted the technique of McKay et al. (2012) where guide camera images are used to calculate the fraction of total light being collected from our standard star. The width of the telluric and Venusian lines are not spectrally resolved by ARCES and are defined by the instrumental spread function. For ARCES, this is described well by a Gaussian function which we fit to each line for deblending.

Although a scaled day side spectrum removes most of the Fraunhofer lines, some residual still exists. To remove this residual, we subtracted a scaled solar spectrum that we obtained from the BASS 2000 database (http://bass2000.obspm.fr/solar_spec-t.php). We then combined spectra that were taken at the same location on Venus to improve our signal to noise ratio. The error bars shown for flux calibrated data are calculated based on detector gain, read noise, Poisson statistics, and telescope transmission, with telescope transmission being the largest of our uncertainties. The scatter in the continuum is calculated and the mean and one standard deviation of the mean are plotted in all panels of Fig. 1.