OXGEN GREEN LINE EMISSION ON VENUS AND ITS CONNECTION TO SOLAR FLARES.
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Abstract: The Venusian nightglow is known to have features that are temporally and spatially variable. However, the reason for variability is unknown. One feature that is particularly variable is the oxygen green line at 557.7 nm. While the terrestrial oxygen line is a constant feature, it was only seen on Venus from 1999 - 2004, during the last solar maximum. We propose that the variability of Venus' green line is due to solar flares, which is an increase in extreme ultraviolet (EUV) photons and charged particles, which could drive some nightglow features. A review of past oxygen green line detections shows a correlation between emission and high-energy solar flares directed at Venus. For every green line detection, there was at least one high-energy flare directed at Venus a week prior to observation. For every non-detection, there were no high-energy flares for a least a month prior. We observed Venus as a Target of Opportunity after an M-class flare was emitted in the direction of Venus on April 17, 2012, UT. We present our results from these observations.

Introduction: Earth, Venus, and Mars were all formed close to the Sun within one AU of each other. While having similar origins of formation, they presently have very different atmospheres due to the divergent evolution of each planet. The two types of atmospheres that emerged were CO_2 dominated and N_2 dominated, each exhibiting different chemistry [1]. The composition and chemical pathways occurring in each atmosphere can be studied by observing nightglow emission.

Nightglow is caused by recombination of atoms into molecules, or electrons with ions, producing excited molecules and atoms, respectively. Venus has several strong nightglow features, including the O (^1S − ^1D) at 557.7 nm (oxygen green line), O_2 Herzberg II system in the visible, O_2 a-X 0-0 IR atmospheric band at 1.27 *μm*, and NO bands in the UV at 190 - 240 nm and 225 - 270 nm. However, not all these features are constant. The oxygen green line is highly temporally and spatially variable [2], a phenomenon which has yet to be explained, but several chemical pathways have been proposed. The O_2 1.27 *μ*m emission is moderately variable [3] while the O_2 Herzberg II band is fairly stable [2, 4, 5, 6].

The oxygen green line was predicted to be detected by the Venera 9 and 10 spacecraft but it was not seen and was placed with an upper limit of 10 R [7]. It was first seen in 1999 by Slanger et al. [5] with an intensity of 150 R, comparable to terrestrial emission, and been repeatedly found by Slanger and colleagues until 2004. Venera observed Venus during a solar minimum. The first green line detection was strong and occurred during solar maximum. It has since decreased as the Sun moved into minimum. It was proposed by Slanger et al. [8] that the variability may be tied to the solar cycle, with increasing emission occurring as the Sun moves into maximum. This may also be the case for other variable features, such as the O_2 band at 1.27 *μ*m which showed a 1-2 order of magnitude difference between Venera observations in 1975 and Keck observations in 1999 by Slanger et al. [5].

The altitude and mechanism responsible for green line emission on Venus is still unknown. On Earth, the green line is due to the Barth mechanism [9], a multi-step chemical process in the mesosphere involving the photodissociation of CO_2 from UV photons. The photons required to dissociate CO_2 are not dependent on solar cycle, thus emission of the green line should be constant if this were the principle source of emission. Given that the green line is highly variable on Venus, this suggests that another mechanism is responsible for emission, which may be occurring in the ionosphere.

One possible mechanism in the ionosphere is discussed by Slanger et al. [8]. They propose that CO_2 first becomes ionized and reacts with oxygen, eventually leading to green line emission. As EUV photons are dependent on solar cycle, with increased intensity during solar maximum, this could explain the flux variability observed in Venus' green line emission, and possibly other nightglow features. Additionally, charged particles may also play a role in emission. Charged particle impacts produce ions that lead to nightglow emission. Venus' ionosphere is maintained by the transport of ions from the day side to the night side, and through electron precipitation. The effectiveness of these two mechanisms varies depending on the solar cycle [10].

Review of past observations by Slanger et al. [2] show the strongest oxygen green line emission observed occurred in 1999, but solar maximum was in 2002. We propose that emission may be due to increased levels of EUV photons and/or charged particles from solar flares. Solar flare events increase with solar activity but occur at random, which could explain the temporal flux variability. The highest energy flares are M- and X-class and would produce the largest effects on nightglow.

Observations: Observations of the night side of Venus were conducted using the ARC Echelle Spectrograph (ARCES) on the Astrophysical Research Consortium 3.5-m telescope at Apache Observatory (APO). ARCES is a high resolution (R ~ 31,500) spectrograph with a spectral coverage from 320 to 1000 nm. A slit size of 1.6" x 3.2" was used, which corresponds to a size of 870 km x 1740 km, or ~ 1.5 x 10^6 km^2.

In order to separate the Venusian green line from the terrestrial, a Doppler shift of 10 km/s is required. We observed Venus on April 1 and 5, 2012 before any high-energy flares occurred, on April 17 and 18 as a Target of Opportunity after an M-class flare, and on April 21 after a coronal mass ejection (CME) impact. The Doppler shift for these observations ranged from -13.3 km/s to -12.8 km/s.

Since 2001, ARCES has been used to observe the Venusian nightglow six times. These three new observation sets increase that number to nine.

Results: We compare solar flare activity with past green line detections and find that for every detection at least one M- or X-class flare was directed at Venus within a week prior to the observation. For observations where the green line was not detected, a high-energy flare did not occur within one month of each observation. Table 1 summarizes the strength of the green line emission, the number of high-energy flares that were directed at Venus within a week of the observation, and the strongest flare that occurred during that week. A strong emission is defined to be over 50% the flux of the terrestrial oxygen green line, a medium strength between 20 - 50%, and weak below 20%.

Conclusions: Table 1 suggests that there is a correlation between flare impacts and oxygen green line nightglow emission on Venus. When the emission was first seen in November 1999, there were two large recent flares, an M 8.0 and an M 7.4. The M 7.4 flare occurred three days prior to the observations, while the M 8.0 flare occurred six days prior. With such a strong emission found after an M-class flare, we would expect to find an equivalent emission strength after the X-class flare on August 27, 2002. However, the strongest flare did not produce the strongest emission. This may be due to the length of time between emission observation and flare occurrence, as it was six days between the X-class flare and the observation. There may also be differences in charged particle densities between the two observations.

Venus was recently hit with an M 1.7 flare on April 16, 2012 (17:24 - 18:00 UT). We observed Venus as a Target of Opportunity on April 17 and 18, 2012 (UT), from APO. We present our results from these most recent observations and discuss the relationship between charged particle impacts on Venus and past green line observations.

Table 1. Number of Flare impacts one week prior to O ($^1S - ^1D$) 5577 Å (oxygen green line) observations.

Obs.	Date (UT)	Emission Strength	Flares	
			#	Max
[2]Keck 1	11/20/99	Strong	11	M 8.0
[2]APO	02/05/01	Medium	1	M 2.4
[2]Keck 1	08/27/02	Medium	9	X 1.0
[2]APO	12/16/02	Weak	3	M 2.5
[2]APO	01/12/03 – 01/17/03	Weak	2	M 4.9
[2]APO	04/28/04	Weak	3	M 2.2
*Keck	07/22/10	**N-D.	0	-
APO	12/21/10 – 12/27/10	N-D	0	-
APO	04/02/12 - 04/06/12	***TBD	0	-
APO	04/17/12 - 04/18/12	TBD	1	M 1.7
APO	04/21/12	TBD	0	-

* Personal Communication
** N.D. = Non-detection
*** TBD = To be determined

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References:

[1] Krasnopolsky V. A. (2011) *Planet. & Spc Sci, 59*, 952. [2] Slanger T. G. et al. (2006) *Icarus, 182*, 1.[3] Crisp D. et al. (1996) *JGR, 101*, 4577. [4] Bougher S. W. and Boruck W. J. (1994) *JGR, 99*, 3759. [5] Slanger T. G. et al. (2001) *Science, 291*, 463. [6] Garcia-Munoz A. et al. (2009) *JGR, 114*, 12002. [7] Krasnopolsky V. A. et al. (1976) *Kosmich. Issled., 14*, 789. [8] Slanger T. G. et al. (2012) *Icarus, 217*, 845. [9] Barth C. A. and Hildebrandt A. F. (1961) *JGR, 66*, 985. [10] Fox J. L and Kliore A. J. (1997) *Venus II, Univ. of AZ*, 161.