Solar Wind Model Supported by Parker Solar Probe Observations During Faint Venusian Auroral Emission

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Abstract

The encounter of the Parker Solar Probe (PSP) with Venus during the Venus Gravity Assist 3 on 2020 July 11 provided a unique opportunity to observe Venus from ground-based facilities on Earth. The Wang–Sheeley–Arge (WSA) model was used to make accurate predictions of solar wind velocity and interplanetary magnetic field polarity at Earth and STEREO-A, as compared to in situ data at each spacecraft. The same model was then used to predict solar wind conditions at Venus. The predictions were in good agreement with in situ PSP data, as they match the overall magnitude and structure of the solar wind velocity and magnetic field at multiple spacecraft. This demonstrates that WSA can be used to make reliable predictions at locations in the heliosphere when in situ data is not available. Venusian aurorae were detected via emission in the oxygen green line OI \( \lambda 5577 \) Å at the same time that PSP captured a heliospheric current sheet sheet crossing, and shortly thereafter, detected an increase in proton count rate. This is the first observation of oxygen green line aurora on Venus that is not the direct result of a coronal mass ejection, a solar flare, or corotating interaction regions.

Unified Astronomy Thesaurus concepts: Solar wind (1534); Venus (1763); Aurorae (2192)

1. Introduction

Solar wind particles flow radially outward from the solar surface, carrying along the frozen-in magnetic field. The slow solar wind, reaching 300–400 km s\(^{-1}\), primarily originates from closed magnetic field lines (those that connect back to the Sun). The fast solar wind, peaking at upwards of 800 km s\(^{-1}\), originates from the open magnetic field lines (those that propagate into the heliosphere) deep within coronal holes. In comparison, coronal mass ejections (CMEs) can vary widely in speeds, from that of the slow solar wind to the fastest solar wind and upwards to several thousands of km s\(^{-1}\) (Gosling et al. 1998).

Particles leaving the Sun from neighboring locations at different speeds result in the formation of stream interaction regions (SIRs). SIRs occur where a high-speed, low-density wind stream interacts with a slow-speed, high-density wind stream (Wood et al. 2009). When the fast stream catches up to the slow stream, the wind compression results in an increase in particle density, magnetic field strength, and a steepening of the velocity profile (Gosling & Pizzo 1999). Corotating interaction regions (CIRs) are then SIRs that have completed one full solar rotation intact.

The expansion of the solar wind carries along the interplanetary magnetic field (IMF), which can be separated into two hemispheres, each defined by whether the magnetic field lines have a direction away from, or toward, the Sun (Wilcox & Ness 1965). The heliospheric current sheet (HCS) is the thin boundary (∼10\(^{8}\) km), present in the 3D interpretation of the solar wind, where there is a change in the connectivity back to the solar surface. This structure extends throughout the solar system and divides the two hemispheres of the IMF. When spacecraft cross the HCS, the in situ measurements of plasma parameters exhibit several characteristic changes. These include a change in polarity of the magnetic field measurements and a change in the directional heat flux signatures in the suprathermal (i.e., strahl) electrons in the solar wind, which stream away from the Sun along magnetic field lines (Feldman et al. 1975). The magnetic field will change from inward to outward (or vice versa), but the strahl electrons will continue to stream away from the Sun. This causes a 180° flip in the strahl electron pitch angle distribution (PAD), describing the relative direction of electron flows and magnetic field lines. HCS crossings are also sometimes associated with an enhancement in proton density and energy (Richardson 2018).

The study of the solar wind is important for planetary science, as solar wind plasma interacts with planets as it flows past them. The evolution of terrestrial planet atmospheres is partially determined by multiple processes, such as atmospheric stripping and particle transport mechanisms. Each of these processes depends on the variations of specific solar wind conditions, such as particle composition, velocity, density, and magnetic field strength. Explosive events on the Sun distribute high-energy particles into the heliosphere and produce pockets of increased plasma densities, increased magnetic field strength, and shocks. These disturbances are known to be one cause of atmospheric emission and strip planetary atmospheres (e.g., McEnulty et al. 2010). The induced auroral emission is one example of an interaction between solar particles and planetary atmospheres.

Nightside diffuse auroral emission on Venus, detected via the oxygen green line OI \( ^1S – ^1D\) at 5577 Å, has been
repeatedly observed during periods of both high and low solar activity (Slanger et al. 2001, 2006, 2012; Gray et al. 2014). The brightest emission is observed during CME passages and, thus, is attributed to higher particle energies. However, faint emission is also present during CIR passages during solar minimum when CMEs and solar flares were not present (Gray et al. 2014; Gray 2015). Additionally, auroral emission from the oxygen 1304 Å line has been previously detected under various solar wind conditions (Phillips et al. 1986; Fox & Stewart 1991). Therefore, the exact particle energy and flux needed to drive Venustian auroral emission are currently unclear.

There have been no dedicated solar wind instruments at Venus since the end of the Venus Express mission in 2014. Spacecraft with solar wind instruments that use Venus for gravity assist maneuvers can be leveraged to provide ad hoc solar wind data in the Venustian environment. One such example is the Parker Solar Probe (PSP), which has seven planned Venus flybys between 2018 and 2024 (Fox et al. 2016). When there are no spacecraft at Venus, solar wind models can be used to describe the solar wind conditions.

In this work, in situ solar wind data captured by PSP during the Venus Gravity Assist (VGA) 3 on 2020 July 11 are compared with solar wind models and ground-based spectral observations of Venustian aurorae. The positions of the terrestrial planets during VGA 3, along with the proximity of PSP to other spacecraft, including the Solar Terrestrial Relations Observatory (STEREO) and Advanced Composition Explorer (ACE), are shown in Figure 1. This work demonstrates, for the first time, the presence of oxygen green line auroral emission on Venus coincident with an HCS crossing. This work shows that solar wind modeling at Venus can be reliable when in situ solar wind data are not available. PSP data from VGA 3 are presented in Section 2.1. A description of the solar wind modeling results is provided in Section 2.2. Section 3 details spectroscopic observations of the Venustian nightside atmosphere. A discussion of the relationship between the solar wind data, modeling, and Venustian spectra is offered in Section 4. Section 5 discusses the implications of the results.

2. Solar Wind Conditions

2.1. Parker Solar Probe Measurements

During the PSP VGA 3, magnetic field data were collected using the Fields Experiment (FIELDS; Bale et al. 2016) and particle data were collected using the Solar Wind Electrons Alphas and Protons Investigation (SWEAP; Kasper et al. 2016) and Integrated Science Investigation of the Sun (IS IS; McComas et al. 2016). The closest approach of PSP to Venus was on 2020 July 11 when PSP was within the Venustian magnetosphere from 3:18 to 4:00 UTC for a total of approximately 42 minutes (Collinson et al. 2021).

The in situ magnetic field, suprathermal (315 eV) electron pitch angle distributions (PADs), and proton energy density are shown during the PSP Venus transit on 2020 July 9–11 in Figure 2. The electron PADs are plotted in measured absolute flux units (Figure 2(a)) and with each time point normalized to enhance directionality and de-emphasize time variation in the flux (Figure 2(b)). The magnetic field strength (Figure 2(c)) shows an increase at ~4:00 UTC on July 11, due to PSP traveling through the magnetotail of Venus, as indicated by the gray shaded region. The azimuth angle (φ) is measured counterclockwise from the antisolunar direction (Figure 2(d)), and the magnetic field is plotted in spherical coordinates with the elevation angle (θ) measured along the ecliptic north–south direction (Figure 2(e)).

The strahl suprathermal electrons are expected to travel along local magnetic field lines away from the Sun. When a spacecraft crosses the HCS, the polarity of the magnetic field changes (from away to toward the Sun or vice versa), but the strahl electrons continue to stream away from the Sun. Thus in the magnetic coordinates of PADs (where the streaming directions of particles are measured from the local magnetic field direction), the strahl electrons appear to switch from 0° to near 360°. On July 11, ~08:00 UTC, just such a combination of magnetic field (Figure 2(d)) and electron PAD signatures occurred (Figures 2(a), (b)), indicating the crossing of the HCS.

During the Venus encounter, PSP had to be off-pointed from the Sun. This results in an elevation in the temperature of one of the two SWEAP electron instruments, requiring that this instrument be turned off. This occurred ~12:00 UTC on 2020 July 10. From this point through the end of the encounter, the limited angular coverage of the strahl electrons results in the lack of data in Figure 2. Nevertheless, the switch of the strahl electron to near 360° is readily observable.

Proton count rates from the Energetic Particle Instrument–Low Energy (EPI-Lo) on IS IS are shown in Figure 2(f). The proton energies are measured by simultaneously requiring a time of flight measurement (using the microchannel plate system) and energy measurement (using the solid state detector system), resulting in a low background elemental composition determination (Hill et al. 2017). The initial onset of the increased proton count rates occurs ~11:00 UTC on July 10 and the most intense activity begins one day later, at ~11:00 UTC on July 11. A data gap prevents observation of the protons after ~12:30 UTC on 2020 July 11. The Venus encounter is highlighted with gray transparent shading and the period associated with the HCS is indicated with dashed, black vertical lines.
2.2. Solar Wind Modeling

When in situ data are unavailable, models can be used to describe the solar wind conditions throughout the heliosphere. The Wang–Sheeley–Arge (WSA) model (Arge & Pizzo 2000; Arge et al. 2004) is a combined empirical and physics-based representation of the solar wind (Owens et al. 2005; McGregor et al. 2008; Wallace et al. 2019) that is an extension of the original model developed by Wang & Sheeley (1990, 1992). This provides predictions of solar wind velocity and IMF polarity at any point in the inner heliosphere using a combination of three models: the potential field source surface (PFSS) model, the Schatten current sheet (SCS) model, and a modified 1D kinematic solar wind propagation model. In short, the PFSS and SCS models are used to derive the coronal magnetic field, which is then propagated out using a kinematic code. The input data for the PFSS model are maps of the photospheric magnetic field, in this case from the Air Force Data Assimilative Photospheric flux Transport (ADAPT) model. The outputs of WSA are global solar wind speeds and IMF polarity throughout the heliosphere.

The ADAPT model is a photospheric flux transport ensemble model that uses data assimilation methods to evolve the photospheric magnetic flux in time (Arge et al. 2010, 2013; Hickmann et al. 2015). It uses a modified version of the flux transport model based on Worden & Harvey (2000), which accounts for well-known surface flow patterns such as differential rotation, meridional flows, and supergranular diffusion to approximate the instantaneous global magnetic flux distribution. Twelve different ensemble members are

![Figure 2. PSP observations during the third Venus encounter. (a) 315 eV electron PAD (color indicates particles per square cm per second); (b) normalized 315 eV electron PAD; (c) magnitude of the magnetic field; (d) azimuth and (e) polar angles of the magnetic field in radial-tangential-normal (RTN) coordinates; (f) 5 minute averages of proton observations energy density are shown as a spectrogram. The dashed black lines bracket the time of the HCS crossing. The gray shading indicates when PSP was in the magnetotail of Venus. Observations ended before 15:00 UTC on 2020 July 11.](image-url)
generated by varying the supergranular diffusion pattern. In turn, this generates a range of possible states (realizations) of the magnetic field on the solar surface that can best describe the overall photospheric flux distribution at a given time. ADAPT makes use of several magnetogram input sources, including those from the Global Oscillation Network Group (GONG). Maps made from GONG magnetograms using the ADAPT model are referred to as AGONG maps throughout this work.

The magnetic field at the photosphere is extrapolated out to the source surface (Altschuler & Newkirk 1969; Schatten et al. 1969), a boundary at which the field is assumed to be radial and open. This PFSS determines the structure of the magnetic field from the photosphere out to the corona at typical distances of 2–5 $R_\odot$. The output of this PFSS model serves as the input to the Schatten current sheet (SCS) model, which derives a more realistic magnetic field configuration in the upper corona. Because plasma $\beta$ is low in the corona, currents can only flow where the magnetic field strength is near zero, which physically translates to where the polarity changes. The SCS model therefore assumes no current flow, except where the radial component of the magnetic field reverses, and therefore, where the polarity flips. The SCS model introduces current sheets by temporarily reorienting the field at the source surface such that the entire field has the same polarity. A potential solution, with the field vanishing at infinity, is then solved for, effectively solving for a magnetic monopole (Schatten 1971). This solution is expanded out to a given radius, typically between 5 $R_\odot$ and 21.5 $R_\odot$, and then the correct polarity is returned to the field lines. This allows for retention of zero current over the volume while allowing for polarity reversals.

While the PFSS model requires the field to be radial at the source surface, the SCS model uses the PFSS radial magnetic field components as its input, and then generates the global magnetic solution, which includes the nonradial components, from the source surface out to infinity. These conflicting boundary conditions cause discontinuities (kinks) in the field lines at the PFSS–SCS interface (i.e., at the source surface). To minimize this effect and derive a more physically realistic model of the magnetic field, an interface surface is implemented below the PFSS outer boundary (McGregor et al. 2008). In this case, the SCS model does not use the radial field components at the outer boundary of the PFSS model as its input—instead, it uses the radial field components at the interface surface, where the field lines have a more natural configuration (i.e., there are still tangential field components), as they are not strictly forced to be purely radial. This significantly reduces, but does not completely remove, the kinks in the modeled field lines.

The empirically derived solar wind velocity and magnetic field polarity from the SCS model are then fed into the modified 1D kinematic code at a fixed outer boundary (5 $R_\odot$), that propagates the solar wind out into the heliosphere, accounting for stream interactions along the way. Given that the SCS model is a static model without gas pressure, having an outer boundary near 5 $R_\odot$ prevents the model from overflattening the current sheet. WSA is used to make 1–7 days advanced predictions (i.e., predictions at a spacecraft based on inputs maps 1–7 days old), with 3 days and 4 days advanced predictions providing the best agreement with near-Earth in situ measurements, as this is the typical propagation time from the Sun to Earth. In comparison, the propagation time is typically 2–3 days for Venus.

In this study, several iterations of WSA were performed with the goal of achieving the best-fit solutions as compared to both ACE and STEREO-A IMF and solar wind velocity in situ data from 2020 July 8–14 (the key period of interest bracketing the PSP/Venus encounter on 2020 July 11). Fifteen different AGONG maps from ±7 days of the encounter were tested as input data. Multiple combinations of interface and source surface radii, both ranging from 2 to 5 $R_\odot$, in increments of 0.5 $R_\odot$ were investigated for each AGONG map. Maps from dates leading up to July 11 are missing a far-side active region, which can produce changes in the global coronal magnetic field solution (MacDonald et al. 2015). Changes in the interface and source surface radii can change (usually slightly) the magnetic field connectivity between the sub-Venus points and the photosphere and thus modify the predicted solar wind speed at Venus.

A single AGONG map from 2020 July 11 was selected, with an interface radius of 2.5 $R_\odot$ and source surface radius of 3.5 $R_\odot$, and where the magnetic field and velocity predictions were most in line with both ACE and STEREO-A data. The approach taken in this study is to use a single input map (as opposed to a time sequence of updated input maps) to predict the solar wind over a complete rotation of the Sun. The advantage of this approach is that it often provides the best overall representation of the global surface magnetic field of the Sun, even for those cases where the map is from a few days in the future, since it allows for far-side active region fields to be included in the ADAPT data. After finding the best overall fit for ACE and STEREO-A, those same input parameters were used to generate WSA solutions at PSP. A drawback to this approach is that model performance tends to deteriorate the further away the solar wind predictions (taking into account travel time) are from the date of the input map used to drive the model. This is due to the evolution of the magnetic field on the solar surface in the intervening period. For example, solar wind parcels departing the Sun on 11 July arrive at Venus (on average) about 3 days later, so the WSA solar predictions at Venus on July 14 tend to be the most reliable with the accuracy of the predictions deteriorating after this date. The same set of maps was tried as a time sequence, (i.e., providing the model with a new map for each day), but as the active region on the far side was not incorporated into each day of the maps, these results did not match in situ data as well.

WSA solar wind predictions at PSP/Venus, ACE/Earth, and STEREO-A using the ADAPT ensemble set of maps from 2020 July 11 are shown in Figure 3. While a single map from the ensemble was used to set the source surface and interface radii, the results from the ensemble are shown in order to provide a better estimate of the uncertainties in the WSA predictions. The left panels indicate IMF polarity and the right panels show solar wind velocity with in situ data shown in black. Blue dots indicate the ensemble average solution, while blue bars bracket the maximum and minimum solutions across all realizations. Periods where the IMF is zero usually indicate a data gap. Occasionally, a zero will indicate a period where the IMF polarity is considered indeterminate. Multiple jumps in IMF polarity over a short period of time usually indicate that the spacecraft is near the HCS.

WSA predictions match the overall magnitude and structure of the solar wind velocity and magnetic polarity when compared to in situ data at multiple spacecraft. WSA captures the peak velocities for dates after July 11, as well as the HCS
crossings around June 28 and July 4. The predictions that are more accurate at Earth do not compare as well with the in situ data at STEREO-A. However, these are still within the margins of the ensemble set of predictions. Because Venus is closer to Earth than STEREO-A (which is that it is located nearly 90° in longitude from Venus as shown in Figure 1), accurate predictions at Earth are more critical than agreement at STEREO-A. Most importantly, the predictions at the location of PSP agree with in situ data just as well as the predictions at Earth. Critically, the predictions at PSP were performed before PSP data were released from the actual encounter.

The large-scale coronal field at 5 \( R_e \) is shown in Figure 4. At 5 \( R_e \), the magnetic field strength values are extremely uniform and merely reflect the field polarity, where light gray indicates a positive polarity and dark gray indicates a negative field polarity. The yellow line shows the heliospheric current sheet.

![Figure 3](image1.png)  
**Figure 3.** WSA model predictions of (left column) coronal magnetic field polarity and (right column) solar wind velocity using an AGONG map of 2020 July 11. From top to bottom: at PSP/Venus, ACE/Earth, and STEREO-A. Black lines show respective in situ spacecraft data. Blue dots indicate the average solution from 12 realizations. Blue bars bracket the maximum and minimum solutions across all realizations. Red bars indicate standard deviation.

![Figure 4](image2.png)  
**Figure 4.** WSA coronal magnetic field polarity predictions at 5 \( R_e \) using an AGONG map of 2020 July 11. Light gray indicates a positive polarity and dark gray indicates a negative field polarity. The yellow line shows the heliospheric current sheet. The red crosses indicate the daily sub-Venus point (the points connecting the center of the Sun to Venus). This is the date when the solar wind leaves the Sun, which would arrive at Venus 2–3 days later. The current sheet is extremely flat in the days bracketing the flyby, July 8–14.
To observe Venusian auroral emission, being less than one-third of the terrestrial emission. Inconclusive data show that there might be emission present, but the detection is near the noise level. Absent refers to data that do not contain any evidence of auroral emission.

The red crosses indicate the daily sub-Venus points. The dates labeled in red indicate the day that the solar wind left the outer boundary (5 R\(_e\)) of the WSA model. It is clear that the current sheet is extremely flat during the period of July 8–14. A parcel of material leaving the Sun with an average solar wind speed of 350 km s\(^{-1}\) reaches Venus in 3.5 days. The solar wind that reached Venus on July 11 would have left the Sun on about July 8, the time at which PSP was extremely close (i.e., less than 5°) to the current sheet, as can be seen in Figure 4.

While the model does not reproduce the current sheet crossing at PSP on July 11, it captures the overall structure of the IMF and solar wind very well, and it is clear that PSP is extremely close to the HCS. The in situ data near July 11 in Figure 3 show that PSP was very close to the current sheet as the polarity flips multiple times over only a few days. This is consistent with the global solution provided by WSA as shown in Figure 4. In the in situ PSP and ACE data, there is a clear shift in polarity near June 29, and again on July 5. The model accurately captures these transitions at both spacecraft. Due to the global nature of the PFSS model, the WSA model is very sensitive to uncertainties in the absolute and relative strengths of the polar fields, which are difficult to accurately measure (Arge & Pizzo 2000). These uncertainties can easily shift the HCS a few degrees. Given how flat the current sheet is at this time, the results are well within the precision of the model.

### 3. Ground-based Observations

During VGA 3, Venus was in favorable conditions to observe from the ground on Earth for auroral emission. This presented a unique opportunity for solar wind data to be collected at the same time as ground-based spectroscopic observations of the planet. Observations of Venus were obtained using the Astrophysical Research Consortium (ARC) 3.5 m telescope at Apache Point Observatory (APO) with the ARC Echelle Spectrograph (ARCES) on 2020 July 11, 12, and 14 UTC. A summary of the observations is provided in Table 1. ARCES is a high resolution (R \(\sim 31,500\)) spectrograph with a wavelength range of 3200–10,000 Å and a slit size of 1′6 × 3′2. To observe Venusian auroral emission, Venus must have a sufficient differential velocity from Earth that allows for separation via a Doppler shift of the Venusian and terrestrial spectral features. For ARCES, this requires a relative velocity of at least 8 km s\(^{-1}\). To minimize the amount of scattered light from the Venusian dayside, Venus is best observed when it is less than half illuminated. During these observations, Venus was in a position that satisfied such conditions, with a relative velocity of 12.1–12.3 km s\(^{-1}\) and 27%–30% illumination, and had an angular diameter of \(\sim 37″\).

For each observation, spectra of both the dayside and nightside of Venus were collected, along with standard calibration exposures. Dayside exposures were taken near the terminator to prevent saturation, and nightside exposures were taken on the limb near the equator. Standard data reduction included using flat-fielding, bias subtraction, and wavelength calibration. The dayside spectra were normalized and subtracted from the normalized nightside spectra to account for scattered light and to remove a majority of the contribution of the Fraunhofer lines. In order to remove the residuals, known solar lines were fit with a Gaussian and subtracted from the spectra. Individual exposures were combined to increase the signal-to-noise ratio.

The strength of the Venusian emission line cannot be flux calibrated, as none of these observations were taken in photometric sky conditions. Instead, a comparison of the relative strength of the Venusian line to the terrestrial emission line is performed. It is noteworthy that the terrestrial green line can fluctuate by twice the mean value over a given night, with greater variability near dawn (Roach & Pettit 1951). Following the nomenclature of Gray et al. (2014), the strength of the Venusian aurora is simply defined by a comparison of the Venusian spectral line to the terrestrial line: weak (\(<33\%)\), medium (33%–66%), and strong (\(>66\%\)). Spectra from 2020 July 11, 12, and 14 are shown in Figure 5. Weak Venusian emission, present on 2020 July 11, may continue just above the noise level through to 2020 July 12, but there is no evidence of auroral emission on 2020 July 14.

### 4. Discussion

The WSA model serves as a robust tool to predict solar wind velocity and IMF polarity at points in the inner heliosphere where in situ data are unavailable. This detailed study provides an example where accurate WSA model predictions at Earth and STEREO-A also result in reliable predictions at Venus as confirmed by PSP during the July 11 encounter of the planet. While the model does not explicitly predict the current sheet crossing at PSP on July 11, it accurately captures the overall structure of the IMF and solar wind. In particular, the in situ data show that the spacecraft was very close to the current sheet for the few days leading up to the time of encounter, as the polarity flips multiple times over this period. The WSA model solution presented in Figure 4 is consistent with this interpretation, as the sub-Venus points reside near the heliospheric current sheet for the entire rotation. In fact, it shows a very close approach on July 8, which would be detected at PSP sometime on July 11. In general, it is especially difficult to accurately predict the solar wind when the current sheet is flat and lies near and parallel to the subsatellite track of a
spacecraft. This is due to the fact that small uncertainties in the sizes and relative magnitudes of the polar fields can easily shift up or down the latitude of the heliospheric current sheet (Arge & Pizzo 2000) as determined by the model. It is well known that the polar field measurements are highly uncertain (Arge et al. 2011), which makes it especially difficult for coronal models to determine the location of the heliospheric current sheet with a high degree of precision.

Given that there are currently no instruments making routine measurements of the solar wind near Venus, accurate modeling of the conditions near the Venusian environment is the only viable option available. Data from spacecraft that constantly monitor the solar wind at multiple locations can be used to improve the reliability of the predictions at other locations in the heliosphere where no in situ data are available. This is particularly useful when some in situ data are within reasonable angular proximity (less than 90°) to Venus. This means that for both future and past detections of the Venusian green line that have no obvious solar activity present (e.g., a CME or solar flare) WSA can be used to determine the solar wind velocity and polarity.

The spectra suggest auroral emission via the oxygen green line on Venus at the same time that PSP undergoes an HCS crossing. This is the first observation of oxygen green line aurora on Venus that is not the direct result of a CME, solar flare, or CIR interaction. The emission here is comparable to the intensity shown in a previous detection (Gray et al. 2014; Gray 2015) where there was weak emission when a dense solar wind stream passed over Venus. In the observations presented in this work, there is no evidence of a compression region, which is typically indicated by overall velocity and density increases. This demonstrates that even low-level solar activity is capable of inducing auroral emission on Venus.

Gray et al. (2018) proposed that the Venusian green line is a unique global diffuse proton aurora. This requires proton energies \( \geq 70 \text{ keV} \) that are directly deposited on the Venusian nightside. Proton energies detected by ACE (near Earth) and extrapolated out to Venus suggest that such protons are present during green line detections on Venus during both solar minimum and maximum (Gray & Kovac 2020). However, there have been no instruments capable of isolating and measuring protons above 12 keV near Venus until PSP (Gray et al. 2021). Previous studies of Venusian aurora in the ultraviolet were thought to be the result of soft energy electrons (Fox & Stewart 1991), but it was not ruled out that another source may be the precipitation of newly ionized particles that are accelerated into the atmosphere (Phillips et al. 1986). The weak detection of the Venusian green line combined with the increase in the count rate of protons \( \geq 70 \text{ keV} \) further strengthens the argument that the Venusian green line is a proton-induced auroral feature.

5. Conclusions

In this work, detection of auroral emission on Venus is presented along with in situ solar wind data and solar wind model predictions during PSP’s third encounter with Venus on 2020 July 11. The WSA model was tested with multiple parameters to provide accurate predictions at Earth and reasonable agreement at STEREO-A when compared to in situ data at each spacecraft. The best photospheric magnetic field input map provided the boundary conditions to WSA to then predict the solar wind at Venus. This also showed good agreement with in situ PSP data. This acts as a single-case demonstration of using WSA to predict solar wind plasma parameters at locations in the heliosphere where no in situ observations are available, as long as the model can be simultaneously validated at multiple locations where in situ observations are available. More specifically, WSA can be used to provide retrospective estimates of the solar wind conditions at Venus during previous Venusian green line auroral detections (and nondetections), even where no in situ spacecraft observations near the planet are available.

The Venusian green line emission presented here is the first observation of Venusian oxygen green line aurora that is not directly associated with a CME, solar flare, or CIR. This further demonstrates that aurorae on Venus are possible even under low-level, ambient solar wind conditions typical of solar minimum. At the time of the emission, PSP observations show a clear HCS crossing. While not previously considered, this work highlights the importance that the HCS may have on the Venusian atmosphere. When Venus encounters a particularly flat HCS, it may cross this boundary several times over a period of hours to days.

The PSP observations also show an increase in protons in the 70–100 keV energy range. This is the first time that an instrument capable of detecting protons in the described energy range has been at Venus. The weak detection of the Venusian green line coupled with the increase of \( \geq 70 \text{ keV} \) protons...
supports the possibility that the Venusian green line aurora is the result of the precipitation of high-energy protons. Future additional observations of Venus are needed to test the viability of this mechanism.

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