The transterminator ion flow at Venus at Solar Minimum

A. G. Wood[1, 2], S. E. Pryse[1], M. Grande[1], I. C. Whittaker[1, 3], A. J. Coates[4], K. Husband[4], W. Baumjohann[5], T. Zhang[5], C. Mazelle[6], E. Kallio[7], M. Fränz[8], S. McKenna-Lawlor[9] and P. Wurz[10]

[1] Institute of Mathematics and Physics, Aberystwyth University, Aberystwyth, Wales, UK

[2] School of Engineering, University of Liverpool, Liverpool, UK

[3] University of St. Andrews, St Andrews, Scotland, UK

[4] Mullard Space Science Laboratory, University College London, UK

[5] Space Research Institute, Austrian Academy of Sciences, Graz, Austria

[6] Institut de Recherche en Astrophysique et Planétologie, Toulouse, France

[7] Finnish Meteorological Institute, Helsinki, Finland

[8] Max-Planck-Institut für Sonnensystemforschung, Katlenburg-Lindau, Germany

[9] Space technology Ltd., National University of Ireland, Ireland

[10] University of Bern, Physikalisches Institut, Switzerland

Abstract

The transterminator ion flow in the Venusian ionosphere is observed at solar minimum for the first time. This antisunward flow, which transports ions from the day to the nightside, is primarily driven by a pressure gradient caused by photoionisation. Although such a flow was been observed previously around solar maximum, at solar minimum the transport process is severely inhibited by the lower altitude of the ionopause. Observations of ionospheric plasma at solar minimum are routinely made by ASPERA-4 onboard the Venus Express spacecraft and constitute the first extensive in-situ measurements of this plasma under these solar conditions. Observations of ions of ionospheric origin showed asymmetries in both the dawn-

dusk and noon-midnight planes for ions of ionospheric origin. Larger numbers of ions are observed on the dusk side than on the dawn side and on the dayside than the nightside, although significant numbers of ions are present nightward of the terminator. Collectively these observations suggest a nightward ion flow with the dawn-dusk asymmetry resulting from variations in the plasma density in the dayside ionosphere. Observations of the ion energies suggest that this flow has a velocity of (2.5 ± 1.5) km s^{-1}. It is suggested that this flow is a significant source of ions for the nightside ionosphere in the terminator region at solar minimum.

Introduction

The nightside ionosphere of Venus has a dynamic and complex structure (Brace et al., 1979). To date the most extensive set of in situ observations of the ionospheric plasma were obtained by Pioneer Venus Orbiter (PVO). Although the PVO mission covered an entire solar cycle the ionospheric measurements were largely restricted to a limited period close to solar maximum between 1978 and 1980 when periapsis was at a sufficiently low altitude to allow sampling of the ionosphere. The solar flux during this period was about 200 solar flux units (sfu). These PVO observations covered all local time sectors. In the nightside ionosphere they showed that precipitating electrons could contribute only ~25 % of the plasma densities observed and that changes in ionospheric densities were much more variable than, and not correlated with, changes in the flux of precipitating electrons (Spenner et al., 1981). Observations of the flux of atomic oxygen ions across the terminator from the day to nightside showed that this ion flux was sufficient to explain the observed ion densities in the nightside ionosphere at solar maximum (Knudsen et al., 1980). The ions were assumed to follow ballistic trajectories and theoretical calculations predicted that 80 % of the ions that crossed the terminator had recombined with electrons before they reached a solar zenith angle

(SZA) of 110^o. Only those ions that crossed the terminator at the highest altitudes reached the central region of the nightside ionosphere. A modelling study by Cravens et al. (1983) predicted that ions which crossed the terminator at altitudes below 500 km recombined before reaching SZA 120^o, whilst ions that crossed the terminator at 876 km influenced the entire night sector. Taken collectively these results showed that the primary source of the nightside ionosphere was plasma transport from the dayside. The plasma flow from the subsolar region toward the nightside is primarily driven by the day-to-night pressure gradient (Knudsen et al., 1981), although whether this plasma followed ballistic trajectories remained an open question. Knudsen et al. (1982) showed that the flow speed across the terminator was highly variable but was typically several kilometers per second. The average value of the antisunward component of the velocity in the terminator region at solar maximum increased with altitude from a few hundred meters per second at an altitude of 150 km to ~4 km s^{-1} at 800 km (Knudsen and Miller, 1992).

The altitude of the ionopause in the terminator region played an important role in the total number of ions transported from the day to the nightside. It's altitude in this region was variable (Elphic et al., 1980) but was typically around 1,000 km (Brace et al., 1983). This variability was attributed to changes in the solar EUV flux and the solar wind dynamic pressure, the balance of which altered the altitude (Knudsen and Miller, 1992). As the ionopause moved to lower altitudes the total number of ions transported antisunward was reduced (Knudsen et al., 1981). Theoretical calculations by Brace et al. (1995) showed that the transterminator flow could transport more ions antisunward than were required to maintain the nightside ionosphere and it was suggested that some of these ions might be lost to the solar wind.

Limited in situ ionospheric observations aboard PVO were made in the pre-dawn sector at low latitudes in 1992 in the declining phase of solar cycle 22 under conditions of moderate solar flux (~120 sfu). The observed ion densities in this sector were significantly larger than those that would be expected in the absence of an antisunward ion flow. This suggested that ion transport was significant in this sector (Brannon et al., 1993). The PVO observations showed that the total transterminator flux was 23 % of that at solar maximum and that the greatest reductions in the number of ions transported antisunward occurred at the highest altitudes (Spenner et al., 1995).

The PVO misson did not include in situ observations of the Venusian ionosphere around solar minimum, however the behaviour of the ionopause was inferred from PVO radio occultation profiles, for which the temporal data coverage was less extensive than for the in situ measurements. The ionopause was at significantly lower altitudes at solar minimum than at solar maximum, typically between 200 km and 300 km for all SZA (Kliore and Luhmann, 1991). The radio occultation profiles from PVO also showed that the transport process was severely inhibited (Knudsen et al., 1987). In contrast radio occultation profiles from Venera 9 and 10 observed the ionopause at higher altitudes in the terminator region at solar minimum with altitudes between 600 km and 800 km (Garvik and Samoznaev, 1987).

Reviewer comment: Page 5 the reference to dawn dusk asymmetry in plasma density driving trans -terminator flow is not clear. There should be trans-terminator flow at both terminators, the asymmetry enhances one but does not essentially drive it. This mistaken view, that the d-d asymmetry by itself is a reason for TT flow is then also misquoted in the discussion below.
My comment: Our intention was to write exactly what the reviewer has said. The modification is shown in bold in the following paragraph.

The Venusian ionosphere exhibited a number of asymmetries between the dawn and dusk sectors. Brace et al. (1982) observed that the ionopause was higher on the dawn side than at dusk due to interaction with the solar wind. Miller and Knudsen (1987) reported larger antisunward velocities within the ionosphere on the dawn side than on the dusk side above an altitude of 400 km, with the pattern reversed below this altitude. The dawn-dusk asymmetry below 400 km was largely attributed to photoionisation as plasma in the post-noon sector had been exposed to sunlight for longer than plasma in the pre-noon sector.

Original text: These enhanced plasma densities resulted in an increased pressure gradient driving the nightward transport of ions.

Modified text: The plasma flow from the dayside to the nightside was driven by the day-to-night pressure gradient and the higher plasma densities in the post-noon sector enhanced the nightward transport of ions on the dusk side.

The super-rotation of the neutral atmosphere also enhanced the ion flow on the dusk side and reduced the flow on the dawn side due to collisional interactions between the ions and the neutral species. A subsequent modelling study at the altitude of the peak density in the ionosphere (~140 km) showed that differences in the thermospheric composition between the dawn and dusk sides may also cause asymmetries in the ionosphere at these altitudes due to changes in the dominant chemical reactions (Fox and Kasprzak, 2007).

Between August 2008 and October 2009 Venus Express (VEX) was in an orbit with periapsis near 86°N and an altitude between 185 km and 215 km with about ~10 minutes spent in the ionosphere during each orbit. Taken collectively over many orbits the in situ ionospheric measurements cover all local time sectors, with each orbit sampling the terminator region at polar latitudes. In the current study these observations are used to determine the plasma distribution near the terminator and to show that the transport process contributes to the maintenance of the nightside ionosphere close to solar minimum.

Instrumentation

Venus EXpress (VEX) is the first European mission to Venus (Titov et al., 2006). The VEX spacecraft was inserted into a near polar orbit in April 2006 and so every orbit sampled the terminator region at polar latitudes. The Analyser of Space Plasmas and Energetic Atoms (ASPERA-4) package on VEX contains an ELectron Spectrometer (ELS), an Ion Mass Analyzer (IMA), a Neutral Particle Detector (NPD) and a Neutral Particle Imager (NPI) (Barabash et al., 2007). In August 2008 periapsis was lowered from an altitude of around 300 km to 185 km, allowing the spacecraft to sample deeper into the ionosphere. Observations made using the IMA sensor once this maneuver had occurred are of particular interest to the present study. This instrument observes the ion energy per charge, E/q, and determines the mass per charge, m/q, of each ion as well as the number of ions observed. It has a 360^o field of view in azimuth and ±45^o in elevation in the spacecraft frame of reference and an energy range of 10 eV to 30 keV. The standard observing mode used during the period considered in this study was a scan in decreasing energy through 96 equal logarithmic steps, observing for 250 ms at each. These measurements were made at all azimuths simultaneously at a given elevation. The elevation angle was then varied through eight positions, which gave a total cycle time of 192 s.

Observations

Reviewers comment: Page 6, serious and fundamental typo: There are lower ion masses in the sheath and higher in the ionosphere. It is so confusing that the low mass channel numbers in the data refer to higher masses, that even the authors get I wrong here. Please proofread the paper more careful.
My comment: Opps. Corrected text in bold.

Data subsequent to the lowering of the periapsis of VEX were considered. One Venus year of data were selected between 4th August 2008 and 17th March 2009 allowing the spacecraft to sample all local time sectors twice as it transited these sectors at high latitudes in opposite directions half a Venusian year apart. Within this interval periapsis was at 86° N. The ion counts as a function of energy observed by the IMA during a spacecraft transit between 04:30 UT and 06:30 UT on 9th August 2008 are shown on a logarithmic scale in the upper panel of Fig. 1. The ion counts as a function of mass channel number are shown in the lower panel of Fig. 1 with lower channel numbers corresponding to higher mass ions (Barabash et al., 2007). These data from 9th August 2008 are considered as an example of how data from the entire year were selected and processed.

Original text:

The data in the lower panel show two clear ion populations; one with a lower ion mass per unit charge observed between 05:28 UT and 05:47 UT and one with a higher ion mass per unit charge observed before and after these times.

Modified text:

The data in the lower panel show two clear ion populations; one with a higher ion mass per unit charge observed between 05:28 UT and 05:47 UT and one with a lower ion mass per unit charge observed before and after these times.

Prior to 04:46 UT and after 06:03 UT the IMA observed ions with energies of some 300 eV - 800 eV (Fig. 1, upper panel) with a low mass to charge ratio (high channel number in Fig. 1, lower panel) indicating that the spacecraft was in the solar wind. In the intervals from 04:46 UT to 05:28 UT and 05:47 UT to 06:03 UT the IMA sensor observed ions over a larger range of energies than observed in the solar wind, from some 200 eV - 1 keV with mass to charge ratios similar to that observed in the solar wind. Taken collectively these data suggested that the spacecraft was in the shocked solar wind, within the bow shock. The observations closest to periapsis, between 05:28 UT and 05:47 UT, showed ions at energies below some 50 eV with higher masses than those observed in the solar wind. These low energy ions were interpreted as being of planetary origin.

Reviewer comment: Page 7 here the ion masses are quoted correctly, but the description of the ICB is superficial and needs to be improved. Sentence "for example in Fig 1 these data are in the pink box" reads very simplistic..
My comment: I have made some small alterations, but cannot really see how to improve this further. Could you advice?

Reviewer comment: Further below: reference to " these ions " and "this subset of data" are unclear. Be more exact.
My comment:Alterations made.

Inspection of the datasets from a large number of orbits showed that it was convenient to define the Ion Composition Boundary (ICB), which marks the transition between the shocked solar wind and the planetary plasma (e.g. Martinecz et al., 2000), by considering the mass channel at which the greatest number of ions was observed in each 192 s cycle. Data for which the mass channel of the maximum ion count was 15 or below were taken to correspond to altitudes below the ICB and these data were considered for further analysis.

Original text:

For example in Fig. 1 these data are within the pink box.

Modified text:

In the example from 9th August 2008 the observations closest to periapsis, between 05:28 UT and 05:47 UT, were interpreted as being below the ICB and are indicated in Fig. 1 as being within the pink box.

The spacecraft velocity at periapsis (~200 km) was ~10 km s^{-1} which was larger than the ion velocities observed by PVO of ~3 km s^{-1} at these altitudes.

Original text:

The velocities of the ions were small compared to the spacecraft and therefore, to ensure the ions were detected, observations were only considered if the ram direction was

within the field-of-view of IMA. This selection criterion meant that observations were only considered when the spacecraft attitude was suitable for observing these ions. The IMA observed in the ram direction for all, or part, of the time when VEX was within the ionosphere on 136 orbits and this sub-set of data were considered for further analysis.

Modified text:

The velocities of the ions were expected to be ~1 km s^{-1} around periapsis (Knudsen and Miller, 1992). The ion velocities were small compared to the velocity of the spacecraft and therefore, to ensure the ions were detected, observations were only considered if the ram direction was within the field-of-view of IMA. This selection criterion meant that observations were only considered when the spacecraft attitude was suitable for observing these ions. The IMA observed in the ram direction for all, or part, of the time when VEX was within the ionosphere on 136 orbits. This sub-set of data (136 orbits out of 225 orbits) were considered for further analysis.

Reviewer comment: Further below: another "this subset of 136 orbits " appears after an unclear description. Subset of how many orbits in total ?
My comment: Partially dealt with in preceding paragraph. Partially dealt with below.

Reviewer comment: Top of page 8: the entire description of what the summed ion counts mean should be sharpened up and made clearer. There are some long sentences, which do not fit together at all in their sub-sentences. This is very unclear language in the entire paragraph. The ion density decrease with altitude is described two times in consequent sentences.
My comment: Paragraph rewritten.

Original text:

In this subset of 136 orbits, for each observing cycle of 192 s, the ion counts at the elevation angle of the maximum number of ions were considered, and the total ion

counts for energies below 100 eV were determined by summing over the energies. These will be referred to as the summed ion counts. The ion counts at a single elevation angle for energies below 100 eV were conducted in 6.5 s. As the spacecraft velocity was ~10 km s^{-1} these summed ion counts were observed over a horizontal distance of some 65 km (0.01 R_v where R_v is the radius of Venus, 6052 km) and are plotted in Venus Solar Orbital (VSO) coordinates in Fig. 2. The positive x-axis is directed towards the Sun and the positive y-axis is orthogonal directed opposite to the orbital velocity direction i.e. pointing towards dawn. As the planet rotates retrograde dawn is in the opposite direction to that observed for the Earth. The largest counts were in the polar region close to periapsis, where the spacecraft sampled the lowest altitudes. In this region the spacecraft was in the topside ionosphere, where the ion density decreases with increasing altitude above the ionisation density peak. In this region the ion density decreases with increasing altitude.

Modified text:

In this subset of 136 orbits ions were observed at eight elevation angles. Counts at the elevation angle of the maximum number of ions were considered, and the total ion counts for energies below 100 eV were determined by summing over the energies. These will be referred to as the summed ion counts. A value for the summed ion counts was determined in every 192 s observing cycle. In each 192 s observing cycle observations were made at eight elevation angles and at 96 energy levels; the ion counts at a single elevation angle for energies below 100 eV were conducted in 6.5 s. As the spacecraft velocity was ~10 km s^{-1} these summed ion counts were observed over a horizontal distance of some 65 km (0.01 R_v where R_v is the radius of Venus, 6052 km). The summed ion counts are plotted in Venus Solar Orbital (VSO) coordinates in Fig. 2. The positive x-axis is directed towards the Sun and the positive y-axis is orthogonal directed opposite

to the orbital velocity direction i.e. pointing towards dawn. As the planet rotates retrograde dawn is in the opposite direction to that observed for the Earth. The largest counts were in the polar region close to periapsis, where the spacecraft sampled the lowest altitudes. In this region the spacecraft was in the topside ionosphere, where the ion density decreases with increasing altitude above the ionisation density peak.

Reviewer comment: Break for a new paragraph at the "However, Fig 2.", and please tell us why you think this Fig shows something contrary to the text before.
(or why else do you use the word "however" here..?)

My comment: Break inserted, “however” removed.

Reviewer comment: Again the entire second half of page 8 needs reformulating and the binning boundaries should be explained more detailed and/or marked in the figures.

My comment: Paragraph ammended.

Original text:

However Fig. 2 exhibits strong asymmetries in both the dawn-dusk and noon-midnight directions. To investigate the dawn-dusk asymmetry, data in a narrow plane aligned dawn-dusk where the x coordinate was restricted to $|x| < 0.2\ R_v$. The observations were then binned into intervals of $0.1\ R_v$ in the y-direction and the median values and quartile values of the ion count in each bin plotted in the upper panel of Fig. 3.

Modified text:

Fig. 2 exhibits strong asymmetries in both the dawn-dusk and noon-midnight directions. To investigate the dawn-dusk asymmetry data were selected from a narrow region aligned with the dawn-dusk axis. This region was centred on the terminator and had a width of $0.2\ R_v$ (the x coordinate was restricted to $|x| < 0.2\ R_v$). The observations were then binned into intervals of $0.1\ R_v$ in the dawn-dusk direction (intervals of $0.1\ R_v$ in the y-direction). The small number of points in bins furthest from the x-axis meant that

bins were combined into intervals of 0.3 R_v to 0.5 R_v and over 0.5 R_v. The median values and quartile values of the ion counts are plotted in the upper panel of Fig. 3.

A strong dawn-dusk asymmetry was observed, with the counts significantly greater on the dusk side that the dawn side by almost an order of magnitude with values of ~6x10^5 on the dusk side and ~5x10^4 around dawn. A similar plot for a noon-midnight narrow plane is shown in the lower panel of Fig. 3 with a restriction that the y coordinate $|y| < 0.2$ R_v and the observations binned into intervals of range between 0.1 R_v and 1 R_v in the x-direction, with the range chosen to ensure a sufficient number of points in each bin. A noon-midnight asymmetry is apparent, with larger counts of ~3x10^5 in the noon sector decreasing rapidly to values of ~5x10^4 in the midnight sector.

Reviewer comment: Please comment on why you think that it is only in the upper quartiles that there are considerable numbers of ions observed night-side of the equator. I will comment on this later in my review.
My comment: We have now dealt with this in the discussion.

However, the upper quartile showed that significant numbers of ions could be present nightward of the terminator (located at x=0) and that these values could be comparable to those in the dayside ionosphere with values of ~8x10^5 recorded in both the day and night sectors.

Reviewer comment: What do you mean by "looking in detail" - please describe your methodology in unique and understandable terms. Energies of what were corrected ? Energies of what cycle ? This is very unscientific language.
My comment: Paragraph amended.
Reviewer comment: You say here that by limiting the altitude to below 500 km you were close to the terminator. Please describe the orbit somewhere and locate the pericenter with respect to the terminator.
My comment: Paragraph amended.
Reviewer comment: Bottom of page 9: Typo "the constant " => "constant"

My comment: Corrected.
Reviewer comment: Following the calculation of energy differences for noon to midnight and midnight to noon orbits, please add a sentence or two about what this means. You jump to the conclusions from here, which comment on this interesting aspect of your data more than a full page later.

My comment: Sentences added.
Original text:

The summed ion counts considered in the described study were for energies below 100 eV but, looking in detail, the energy at which the largest number of ions occurred could also be determined. The energies were also corrected for the spacecraft potential using the method of Coates et al. (2008) based on the analysis of the ionospheric photoelectron peaks and these were taken as a proxy for the energies of each cycle. To investigate ion flow in the terminator region an additional constraint was imposed and only those observations at an altitude of 500 km or lower were considered so as to restrict the observations to near the terminator (within ~30^{o} latitude of the terminator). The data were divided into four bins depending upon the direction of travel of the spacecraft;

- **Spacecraft travelling essentially from noon-to-midnight (within 45^{o} of this direction);**
- **Spacecraft travelling essentially from midnight-to-noon (within 45^{o} of this direction);**
- **Spacecraft travelling essentially from dawn-to-dusk (within 45^{o} of this direction);**
- **Spacecraft travelling essentially from dusk-to-dawn (within 45^{o} of this direction).**

The spacecraft velocity at periapsis was essentially the constant for all observations, with a mean value of (9.78 ± 0.01) km s^{-1}. For each bin the median value of the observed energy was determined. This was (11 ± 3) eV in the noon-to-midnight bin and (20 ± 4) eV in the midnight-to-noon bin, with the uncertainties set by the upper and lower quartiles. For both the dawn-to-dusk and dusk-to-dawn bins the energies were (18 ± 4) eV.

Modified text:

The summed ion counts considered in the preceding paragraphs were for energies below 100 eV. The energy at which the largest number of ions occurred could also be determined. This value was also corrected for the spacecraft potential using the method of Coates et al. (2008) based on the analysis of the ionospheric photoelectron peaks and these were taken as a proxy for the energies of each cycle. To investigate ion flow in the terminator region an additional constraint was imposed and only those observations at an altitude of 500 km or lower were considered. Periapsis was close to 86 ^{o}N throughout the study period and the study contained one Venus year of data. The restriction to only consider observations at an altitude of 500 km or lower meant that observations were considered within ~30^{o} latitude of the pole. The data were divided into four bins depending upon the direction of travel of the spacecraft;

- **Spacecraft travelling essentially from noon-to-midnight (within 45^{o} of this direction);**
- **Spacecraft travelling essentially from midnight-to-noon (within 45^{o} of this direction);**
- **Spacecraft travelling essentially from dawn-to-dusk (within 45^{o} of this direction);**
- **Spacecraft travelling essentially from dusk-to-dawn (within 45^{o} of this direction).**

The spacecraft velocity at periapsis was essentially constant for all observations, with a mean value of (9.78 ± 0.01) km s^{-1}. For each bin the median value of the observed energy was determined. This was (11 ± 3) eV in the noon-to-midnight bin and (20 ± 4) eV in the midnight-to-noon bin, with the uncertainties set by the upper and lower quartiles. The larger ion energies in the midnight-to-noon bin suggested that these ions had a velocity

component that was antiparallel to the spacecraft direction of travel and the smaller values in the noon-to-midnight bin suggested that these ions had a component of velocity which was parallel to the spacecraft direction of travel; both of these observations suggest that the ions travelled in the noon-to-midnight direction. For both the dawn-to-dusk and dusk-to-dawn bins the energies were (18 ± 4) eV. As the difference in the ion energies of these bins was zero this suggested that there was no net ion flow in this direction.

Discussion

Overview: I have revised the discussion. Previously we started with the ion counts and then went to ion energies. The new thread is:

- Ion energies provide evidence for the transterminator flow.
- The dawn-dusk asymmetry in ion counts is consistent with this interpretation.
- Variability in the ion counts in the noon-midnight plane shows that this flow is highly variable.

All of the reviewers comments on the discussion are noted below.

Reviewer comment: Page 10 top: here you say that DD asymmetry in plasma density by itself is a sign for trans-terminator flow. I don't think so, it is at most an indicator for asymmetric T-T flow, if there is any. But it is not a proof for T-T flow in itself.

My comment: It was not meant to be a proof of the transterminator flow. The new form of the discussion should make this clear.

Reviewer comment: In the description of figure 2 you refer to that the last point (No 4) is lower because of increasing S/c altitude. Then the other points should decrease as well away from the Terminator, but they don't. Actually the third one is the highest ! Why ?

My comment: Now detailed in discussion.

Reviewer comment: Page 11: again please describe in more exact terminology what you mean by "energies identified as proxies for the energies of each cycle" - this reads like a proxy description, at best.

My comment: Clarity improved.

Reviewer comment: Later on this page you correctly discuss the observation of energy differences in the two principal orbit directions. This is a good finding of the paper. Please add a sentence from this discussion to the observation section to prepare this discussion for the reader.

My comment: Done.

The major comment from the reviewer was:
Your last sentence [of the discussion], however, summarises the dilemma of this paper. "Taken collectively these observations indicate a night-ward flow across the terminator at solar minimum."
Here I strongly disagree with you here. Taken collectively your data shows that most of the time there is no trans-terminator flow during solar minimum. However, even at solar minimum some transient flow and density variations can be expected to occur in the solar wind, which might reach values of the solar wind conditions during solar maximum, and thus it appears to me that in your upper quartiles you have included some of these solar wind episodes, which are uncharacteristic of solar minimum solar wind conditions. So your conclusions seem to be not valid.

My comment: We were not trying to say that this ALWAYS happens at solar minimum, just that it CAN happen at solar minimum. It is certainly true that, even at solar minimum, more active conditions occur and it is likely that these times are when the transterminator flow occurs. But this is still solar minimum. The rewritten discussion should make this clear.

Original text:

A dawn-dusk asymmetry in the Venusian ionosphere has been reported by Miller and Knudsen (1987) with larger plasma densities observed in the dusk sector. That study, which was conducted at low- and mid-latitudes around solar maximum, attributed the difference to plasma transport with higher density plasma drawn antisunward (nightward) from the post-noon sector. In the present study the dawn-dusk asymmetry (Fig. 3, upper panel) was consistent with their interpretation and it is therefore proposed that an antisunward ion flow occurred across the terminator at high latitudes at solar minimum. The asymmetry observed in the noon-midnight plane (Fig. 3, lower panel) was also consistent with this interpretation with the median values of the three points immediately sunward of the terminator showing the largest values. The point immediately nightward of the terminator was also of a similar value, suggesting that photoionisation may be a source of these ions. The lower value of ~$8x10^4$ on the dayside at 0.4 R_v was a likely consequence of the spacecraft sampling at higher altitudes where the ion densities were expected to be lower. Sunward of 0.5 R_v no data points were

recorded, a likely consequence of the altitude of the ionopause falling to 200 km - 300 km on the dayside (Kliore and Luhmann, 1991) and the spacecraft sampled above these altitudes when it was located ~0.3 R_V sunward of the terminator. In the midnight sector at distances of less than 0.3 R_V nightward of the terminator the median values were lower than those in the noon sector by almost an order of magnitude. However, the upper quartile values in the midnight sector were comparable to the upper quartile values in the noon sector for points within 0.3 R_V of the terminator. This showed that, while ion counts nightward of the terminator were generally lower than those observed on the dayside as expected in the absence of a plasma source, in a significant number of cases the ion counts nightward of the terminator were comparable to the values in the dayside ionosphere. This indicated that, at certain times, a process was acting to maintain the nightside ionosphere.

The ion energies identified as proxies for the energies of each cycle also suggested the nightward transport of ions. When the spacecraft trajectory was close to the midnight-to-noon direction the ion energies were larger than those observed in the noon-to-midnight direction. The larger energies suggested that these ions had a velocity component that was antiparallel to the spacecraft direction of travel, with the smaller values suggesting that these ions had a component of velocity which was parallel to the spacecraft direction of travel. In the dawn-dusk direction the difference in the ion energies was zero suggesting that there was no net ion flow in this direction. Therefore the observed ion energies suggested an ion flow in the noon-to-midnight direction. As the spacecraft velocity at periapsis was the same for orbits in the midnight-to-noon and noon-to-midnight directions the difference in energy of (9 ± 7) eV between observations in these two directions of travel suggested a nightward ion velocity of (2.5 ± 1.5) km s^{-1},

assuming, as did Knudsen and Miller (1992), that the ions are primarily singly ionisaed oxygen. Although it is appreciated that there are substantial uncertainties in this velocity and that the IMA was operating close to the lowest energies it could observe, this velocity is in broad agreement with Knudsen and Miller (1992) who reported antisunward ion flows of some ~3 km s^{-1} at these altitudes.

Taken collectively these observations indicate a nightward ion flow across the terminator at solar minimum, and that this transterminator flow contributes to the maintenance of the nightside ionosphere.

Revised text:

The ion energies suggested the nightward transport of ions. The energy at which the largest number of ions occurred was determined. When the spacecraft trajectory was close to the midnight-to-noon direction the ion energies were larger than those observed in the noon-to-midnight direction. The larger energies suggested that these ions had a velocity component that was antiparallel to the spacecraft direction of travel, with the smaller values suggesting that these ions had a component of velocity which was parallel to the spacecraft direction of travel. In the dawn-dusk direction the difference in the ion energies was zero suggesting that there was no net ion flow in this direction. Therefore the observed ion energies suggested an ion flow in the noon-to-midnight direction. As the spacecraft velocity at periapsis was the same for orbits in the midnight-to-noon and noon-to-midnight directions the difference in energy of (9 ± 7) eV between observations in these two directions of travel suggested a nightward ion velocity of (2.5 ± 1.5) km s^{-1}, assuming, as did Knudsen and Miller (1992), that the ions are primarily singly ionisaed oxygen. Although it is appreciated that there are substantial uncertainties in

this velocity and that the IMA was operating close to the lowest energies it could observe, this velocity is in broad agreement with Knudsen and Miller (1992) who reported antisunward ion flows of some ~3 km s^{-1} at these altitudes.

A dawn-dusk asymmetry in the Venusian ionosphere has been reported by Miller and Knudsen (1987) with larger plasma densities observed in the dusk sector. That study, which was conducted at low- and mid-latitudes around solar maximum, attributed the difference to plasma transport with higher density plasma drawn antisunward (nightward) from the post-noon sector as a transterminator flow. In the present study the dawn-dusk asymmetry (Fig. 3, upper panel) was consistent with their interpretation.

The asymmetry observed in the noon-midnight plane (Fig. 3, lower panel) suggested that the transterminator flow was highly variable. The median values of the three points immediately sunward of the terminator showed the largest values. These median values fell rapidly nightward of the terminator, as expected in the absence of a plasma source. The lower median value of ~$8x10^4$ on the dayside at 0.4 R_v was a likely consequence of the spacecraft sampling at higher altitudes where the ion densities were expected to be lower. Sunward of 0.5 R_v no data points were recorded, a likely consequence of the altitude of the ionopause falling to 200 km - 300 km on the dayside (Kliore and Luhmann, 1991) and the spacecraft sampled above these altitudes when it was located ~0.3 R_v sunward of the terminator. The upper quartile values varied greatly between adjacent bins however upper quartile values in the nightside at a distance of less than 0.5 R_v nightward of the terminator were similar to, or greater than, the median values on the dayside. This suggested that, while ion counts nightward of the terminator were generally lower than those observed on the dayside as expected in the absence of a

plasma source, in a substantial number of cases the ion counts nightward of the terminator were comparable to the values in the dayside ionosphere. This indicated that, at certain times, a process was acting to maintain the nightside ionosphere.

In summary the observations of ion energies indicate that a nightward ion flow across the terminator at solar minimum can occur. The ion counts show that such a flow is highly variable but, at certain times, it contributes to the maintenance of the nightside ionosphere.

Conclusions

In situ ion observations made by the ASPREA-4 experiment onboard the Venus Express spacecraft at solar minimum have shown dawn-dusk and noon-midnight asymmetries. In the former there were a larger number of ions observed on the dusk side. This was consistent with the antisunward transport of ions with plasma densities being larger in the post-noon sector than pre-noon at low-latitudes. In the noon-midnight case the larger number of ions were on the dayside, but substantial numbers of ions were observed nightward of the terminator, indicating that a process maintained the ionosphere at night again consistent with antisunward flow. The difference in ion energies observed when the spacecraft trajectory was directed from noon to midnight compared to when it was directed from midnight to noon suggested an antisunward transterminator flow of (2.5 ± 1.5) km s^{-1}. Collectively these observations indicated that day-to-night plasma transport plays a significant role in the Venusian ionosphere in the terminator region at solar minimum.

Acknowledgements

The authors would like to thank the ASPERA-4 team for their extensive work planning, constructing and operating these instruments on the Venus Express spacecraft, and the subsequent dissemination of these data. The assistance of Neville Shane from Mullard Space Science Laboratory, University College London in implementing software tools at Aberystwyth University is gratefully acknowledged. Financial support for this paper was provided by the UK Science and Technology Facilities Council under grant PP/E001157/1.

Bibliography

Barabash, S., J.-A. Sauvaud, H. Gunell, H. Andersson, A. Grigoriev, K. Brinkfeldt, M. Holmström, R. Lundin, M. Yamauchi, K. Asamura, W. Baumjohann, T.L. Zhang, A.J. Coates, D.R. Linder, D.O. Kataria, C.C. Curtis, K.C. Hsieh, B.R. Sandel, A. Fedorov, C. Mazelle, J.-J. Thocaven, M. Grande, Hannu E.J. Koskinen, E. Kallio, T. Säles, P. Riihela, J. Kozyra, N. Krupp, J. Woch, J. Luhmann, S. McKenna-Lawlor, S. Orsini, R. Cerulli-Irelli, M. Mura, M. Milillo, M. Maggi, E. Roelof, P. Brandt, C.T. Russell, K. Szego, J.D. Winningham, R.A. Frahm, J. Scherrer, J.R. Sharber, P. Wurz, P. Bochsler, The Analyser of Space Plasmas and Energetic Atoms (ASPERA-4) for the Venus Express mission, *Planet. Space Sci.*, *55*, 1772-1792, doi:10.1016/j.pss.2007.01.014, 2007.

Brace, L. H., R. E. Hartle, R. F. Theis, The nightward ion flow scenario at Venus revisited, *Adv. Sp. Res., 16(6)*, 99-112, 1995.

Brace L. H., H. A. Taylor, Jr., T. I. Gombosi, A. J. Kilore, W. C. Knudsen and A. F. Nagy, The ionosphere of Venus: Observations and their interpretation, in Venus, ed. D.M. Hunten, L. Colin, T.M. Donahue and V.I. Moroz, *The University of Arizona Press*, 1983.

Brace, L. H., R. F. Theis and W. R. Hoegy, Plasma clouds above the ionopause of Venus and their implications, *Planet. Space Sci.*, *30*, 29-37, 1982.

Brace, L. H., H. A. Taylor, P. A. Cloutier, R. E. Daniell, and A. F. Nagy, On the Configuration of the Nightside Venus Ionopause, *Geophys. Res. Letts.*, *6*, 345-348, doi:10.1029/GL006i005p00341, 1979.

Brannon, J. F., J. L. Fox, and H. S. Porter, Evidence for Day-to-Night Ion Transport at Low Solar Activity in the Venus Pre-Dawn Ionosphere, *Geophys. Res. Lett.*, *20*, 2,739-2,742, doi:10.1029/93GL02422, 1993.

Coates, A.J., R. A .Frahm, D. R. Linder, D. O. Kataria, Y Soobiah, G. Collinson, J. R. Sharber, J. D. Winningham, S. J. Jeffers, S. Barabash, J. –A. Sauvaud, R. Lundin, M. Holmström, Y. Futaana, M. Yamauchi, A. Grigoriev, H. Andersson, H. Gunell, A. Fedorov, J. –J. Thocaven, T. Zhang, W. Baumjohann, E. Kallio, H. Koskinen, J. U. Kozyra, M. W. Liemohn, Y. Ma, A. Galli, P. Wurz, P. Bochsler, D. Brain, E. C. Roelof, P. Brandt, N. Krupp, J. Woch, M. Fraenz, E. Dubinin, S. McKenna-Lawlor, S. Orsini, R. Cerulli-Irelli, A. Mura, A. Milillo, M. Maggi, C. C. Curtis, B. R. Sandel, K. C. Hsieh, K. Szego, A. Asamura, and M. Grande, Ionospheric Photoelectrons at Venus: Initial Observations by ASPERA-4 ELS, *Planet. Space Sci.*, *56 (6)*, 802-806, May 2008.

Cravens, T. E., S. L. Crawford, A. F. Nagy and T. I. Gombosi, A two dimensional model of the ionosphere of Venus, *J. Geophys. Res.*, *88*, 5,595-5,606, doi:10.1029/JA088iA07p05595, 1983.

Elphic, R., C. Russell, J. Slavin, and L. Brace, Observations of the Dayside Ionopause and Ionosphere of Venus, *J. Geophys. Res.*, *85*, 7679-7696, doi:10.1029/JA085iA13p07679, 1980.

Fox J. L. and W. T. Kasprzak, Near-terminator Venus ionosphere: Evidence for a dawn/dusk asymmetry in the thermosphere, *J. Geophys. Res.*, *112,* E09008, doi:10.1029/2007JE002899, 2007.

Gavrik, A. L. and L. N. Samoznaev, Peculiarities in the dayside ionosphere of Venus during years of high and low solar activity, *Cosmic Research, 25 (2),* 228-232, 1987.

Kliore, A. J. and J. G. Luhmann, Solar cycle effects on the structure of the electron density profiles in the dayside ionosphere of Venus, *J. Geophys. Res.*, *96*, 21,281-21,289, doi:10.1029/91JA01829, 1991.

Knudsen, W. C. and K. L. Miller, The Venus Transterminator Ion Flux at Solar Maximum, *J. Geophys. Res.*, *97*, 17,165-17,167, doi:10.1029/92JA01460, 1992.

Knudsen, W. C., A. J. Kilore and R. C. Whitten, Solar cycle changes in the ionisation sources of the nightside Venus ionosphere, *J. Geophys. Res.*, *92*, 13,391-13,398, doi:10.1029/JA092iA12p13391, 1987.

Knudsen, W. C., P. M. Banks, and K. L. Miller, A new concept of plasma motion and planetary magnetic field for Venus, *Geophys. Res. Lett.*, *9*, 765-768, doi:10.1029/GL009i007p00765, 1982.

Knudsen, W., K. Spenner, and K. Miller, Anti-Solar Acceleration of Ionospheric Plasma across the Venus Terminator, *Geophys. Res. Letts.*, *8*, 241-244, doi:10.1029/GL008i003p00241, 1981.

Knudsen, W. C., K. Spenner, K. L. Miller and V. Novak, Transport of ionospheric O+ ions across the Venus terminator and implications, *J. Geophys. Res.*, 85, 7803-7810, doi:10.1016/0273-1177(87)90207-9, 1980.

Martinecz, C., M. Fränz, J. Woch, N. Krupp, E. Roussos, E. Dubinin, U. Motschmann, S. Barabash, R. Lundin, M. Holmström, H. Andersson, M. Yamauchi, A. Grigoriev, Y. Futaana, H. Gunell, R.A. Frahm, J.D. Winningham, J.R. Sharber, S.J. Jeffers, A.J. Coates, Y. Soobiah, D.R. Linder, D.O. Kataria, G. Collinson, E. Kallio, H. Koskinen, J.U. Kozyra, M.W. Liemohn, Y. Ma, J. Luhmann, E.C. Roelof, P. Brandt, C.C. Curtis, K.C. Hsieh, B.R. Sandel, M. Grande, J.-A. Sauvaud, A. Fedorov, J.-J. Thocaven, S. McKenna-Lawler, S. Orsini, R. Cerulli-Irelli, M. Maggi, A. Mura, A. Milillo, P. Wurz, A. Galli, P. Bochsler, K. Asamura, K. Szego, T. Zhang, and W. Baumjohann, Location of the bow shock and ion composition boundaries at Venus-initial determinations from Venus Express ASPERA-4, *Planet. Space Science 56*, 780-784, 2008 .

Miller, K. L. and W. C. Knudsen, Spatial and temporal variations of the ion velocity measured in the Venus ionosphere, *Adv. Sp. Res., 7(12),* 107-110, doi:10.1016/0273-1177(87)90207-9, 1987.

Spenner, K., W. Knudsen, and W. Lotze, Ion Density, Temperature, and Composition of the Venus Nightside Ionosphere During a Period of Moderate Solar Activity: Implications for Maintaining the Central Nightside, *J. Geophys. Res., 100,* 14,499-14,506, doi:10.1029/95JA01470, 1995.

Spenner, K., W. Knudsen, R. Whitten, P. Michelson, K. Miller, and V. Novak, On the Maintenance of the Venus Nightside Ionosphere: Electron Precipitation and Plasma Transport, *J. Geophys. Res., 86,* 9170-9178, doi:10.1029/JA086iA11p09170, 1981.

Titov, D. V.. H. Svedhem, D. Koschny, R. Hoofs, S. Barabash, J.-L. Bertaux, P. Drossart, V. Formisano, B. Häusler, O. Korablev, W.J. Markiewicz, D. Nevejans, M. Pätzold, G. Piccioni, T.L. Zhang, D. Merritt, O. Witasse, J. Zender, A. Accomazzo, M. Sweeney, D. Trillard, M. Janvier, A. Clochet Venus Express science planning *Planet. Space Sci., 54,* 1279–1297, doi:10.1016/j.pss.2006.04.017, 2006.

Captions

Figure 1 – Ion counts as a function of energy (upper panel) and mass channel number (lower panel) observed by Venus Express (VEX) Ion Mass Analyzer (IMA) between 04:30 UT and

06:30 UT on 9th August 2008. Lower mass channel numbers correspond to ions with a higher mass to charge ratio. Data within the pink box correspond to observations below the Ion Composition Boundary (ICB).

Figure 2 – Summed ion counts for observations at altitudes below the ICB for one Venus year between 4th August 2008 and 17th March 2009 in Venus Solar Orbital (VSO) coordinates. The positive x-axis is directed towards the Sun and the positive y-axis is directed towards dawn.

Figure 3 – Summed ion counts in a narrow plane aligned dawn-dusk (upper panel) and in a narrow plane aligned noon-midnight (lower panel) planes between 4th August 2008 and 17th March 2009 as a function of distance from the pole of the planet. Observations below the ICB for which the x coordinate is $|x| < 0.2\ R_v$ were used for the dawn-dusk plane and observations below the ICB for which the y coordinate is $|y| < 0.2\ R_v$ were used for the noon-midnight plane.