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Are periodic solar wind number density structures formed in the solar corona?

N. M. Viall

Harlan E. Spence
Boston University, harlan.spence@unh.edu

J. Kasper

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Nicholeen M. Viall,[1] Harlan E. Spence,[1] and Justin Kasper[2]

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[1] We present an analysis of the alpha to proton solar wind abundance ratio (A_{He}) during a period characterized by significant large size scale density fluctuations, focusing on an event in which the proton and alpha enhancements are anti-correlated. In a recent study using 11 years (1995–2005) of solar wind observations from the Wind spacecraft, N. M. *Viall et al.* [2008] showed that periodic proton density structures occurred at particular radial length-scales more often than others. The source of these periodic density structures is a significant and outstanding question. Are they generated in the interplanetary medium, or are they a relic of coronal activity as the solar wind was formed? We use A_{He} to answer this question, as solar wind elemental abundance ratios are not expected to change during transit. For this event, the anti-phase nature of the A_{He} variations strongly suggests that periodic solar wind density structures originate in the solar corona. **Citation:** Viall, N. M., H. E. Spence, and J. Kasper (2009), Are periodic solar wind number density structures formed in the solar corona?, *Geophys. Res. Lett.*, *36*, L23102, doi:10.1029/2009GL041191.

1. Introduction

[2] Studies of time series of solar wind proton density measurements at 1 AU have identified fluctuations with significant power at discrete periodicities with timescales of minutes to tens of minutes [e.g., *Kepko et al.*, 2002; *Kepko and Spence*, 2003]. During these intervals of significant periodic density fluctuations, the solar wind velocity remained relatively steady while the magnetic field variations broadly maintained the structures in pressure balance, suggesting that these were static, convecting structures rather than propagating waves [*Kepko et al.*, 2002; *Kepko and Spence*, 2003]. The observation of broad pressure balance does not alone eliminate the possibility of obliquely propagating slow mode waves. However, other characteristics of their events, such as the presence of repeatable, multiple discrete frequencies, are inconsistent with slow mode waves and led them to interpret the observations as non-propagating structures, as we will in this letter.

[3] *Viall et al.* [2008] performed a rigorous spectral analysis on hundreds of thousands of short (~6 hours) data segments for 11 years of solar wind number density data measured by the Solar Wind Experiment (SWE) Faraday Cups on the Wind spacecraft [*Ogilvie et al.*, 1995]. Their study used the instantaneous solar wind velocity measurements to convert the observations from a time series to a radial-length series. They identified statistically significant radial wavelengths in those data segments, and found that periodic density structures occurred at particular radial length-scales more often than at others. The solar wind is a turbulent medium, and intermittent turbulent fluctuations could account for individual occurrences of statistically significant periodic density structures. However, by definition, turbulence is a scale-free process and no particular discrete wavelength should occur more often than others; the probability distribution should be smooth and featureless. The observation of particular radial length-scales occurring more often than others thus requires some other organizing physical process.

[4] It is important for the understanding of solar wind variability to determine if these fluctuations are generated during transit from the corona to 1 AU, or if they are signatures of a process occurring in the corona in the formation of the solar wind. Periodic density structures could be created through local compressive processes; given the observed plasma and magnetic field behavior discussed in the work mentioned above, it is not obvious what that local process would be. An alternative explanation is that these structures form in the solar corona, are frozen into the solar wind, and convect out to Earth.

[5] Larger scale plasmoids have been observed in the corona [e.g., *Sheeley et al.*, 2009] and it is plausible that smaller, quasi-periodic structures may exist as well. *Endeve et al.* [2004] investigated one possible coronal generation mechanism of larger periodic density structures. With their MHD model of the corona, they found that the closed magnetic flux in the helmet streamer is initially too small to balance the thermal pressure gradient across the open-closed magnetic field boundary. This results in plasma expansion, magnetic reconnection at the tip of the helmet streamer and subsequent release of plasmoids into the solar wind, repeating with a periodicity of 13.5 hours. Though their model's periodicity and plasmoid size have larger scale sizes than the solar wind density structures, a similar process that occurs on smaller spatial and temporal scales is not unreasonable, and could lead to the scale sizes given by *Viall et al.* [2008, 2009].

[6] Analysis of the solar wind alpha to proton abundance ratio (A_{He}) during periodic number density structure events can address whether they were formed locally in the solar wind, or in the corona. Elemental abundance ratios in the solar wind provide information about source regions in the corona because they are not easily modified during transit. In particular, A_{He} is useful for this study due to the availability of measurements with time resolution of minutes. In an average sense, A_{He} is known to vary as a function of solar

[1]Department of Astronomy and Center for Space Physics, Boston University, Boston, Massachusetts, USA.
[2]Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts, USA.

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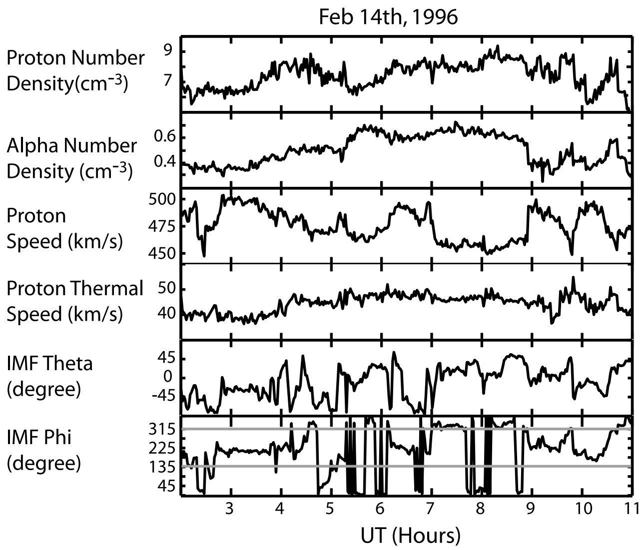

Figure 1. Event overview: time series of the proton density, alpha density, proton speed, proton thermal speed, IMF θ, and IMF φ. The typical IMF φ direction is indicated in grey.

cycle and proton speed [e.g., *Aellig et al.*, 2001; *Kasper et al.*, 2007]. Variability in the solar wind A_{He} is well known to be associated with structure in the corona where that solar wind plasma originates; changes on short time scales (hours) imply spatial or temporal changes in the coronal A_{He} [e.g., *Borrini et al.*, 1981, 1983]. High speed streams are associated with coronal holes and high A_{He} ($\sim$5%), while slow solar wind is associated with low A_{He} (<3%), and ICMEs are associated with very high A_{He} (>8–35%) [*Borrini et al.*, 1983]. Well known is an anticorrelation between A_{He} and the proton number density in relationship to the HCS [*Borrini et al.*, 1981; *Gosling et al.*, 1981]. *Suess et al.* [2009] confirmed those results and showed that the A_{He} depletion near the HCS was indicative of plasma originating from the helmet streamer core. Motivated by these and other observed patterns in $A_{He,}$ *Kasper et al.* [2007] report a linear relationship between the observed proton speed and A_{He}, during periods of low solar activity.

[7] Compressive mechanisms typically found in the interplanetary medium at 1 AU such as turbulence, CIRs and fast-mode shocks could generate structures in the proton and alpha density. These can generate density enhancements in the protons; they will either also compress the alpha particles or not affect the alphas. They will not, on the other hand, deplete the alpha density while they enhance the proton density. Conversely, slow mode waves could produce periodic enhancements in the protons that are in antiphase with enhancements in the alpha density (J. V. Hollweg, personal communication, 2009). We eliminate this possibility in the next section; thus, for this event, periodic density structures in which the proton and alpha density (and therefore A_{He}) are in antiphase suggest that those structures were generated in the solar corona. We have looked for and identified events in which the proton density enhancements previously reported by *Viall et al.* [2008] are anticorrelated with alpha density enhancements. We present one such event in this letter, and demonstrate that at least this example of a periodic density structure was not created in the interplanetary medium. Rather, it was generated in the corona and then convected out to 1 AU, largely unprocessed.

2. Event Analysis

[8] We chose a representative event from the 11-year event list presented by *Viall et al.* [2008] and performed a detailed analysis of the alpha density data. This event occurred between 4.5–9.5 UT, on Feb 14th, 1996, during the previous solar minimum when the linear dependence of A_{He} on speed reported by *Kasper et al.* [2007] is valid. We used the ion measurements made by the SWE Faraday Cups [*Ogilvie et al.*, 1995] (dataset details are described by *Kasper et al.* [2006]) and magnetic field data from the Magnetic Field Investigation [*Lepping et al.*, 1995], averaged over the ion measurement, on the Wind spacecraft. Figure 1 summarizes the interval surrounding the event from 2–11 UT on Feb 14th, 1996. Figure 1 shows the proton number density, the alpha number density, the proton speed, the proton thermal speed, and the two magnetic field angles θ and φ. The angle θ is the angle of the magnetic field out of the xy-plane, and φ is the angle that the magnetic field makes with the x-axis in the xy-plane, both in GSE coordinates.

[9] The solar wind speed during this event is moderate, ranging between 450 and 500 km/s. The angle φ is often near 45° or 225°, a configuration perpendicular to the typical IMF configuration (the typical IMF φ is 135° or 315°, denoted with grey lines in Figure 1, bottom). This non-standard IMF configuration is indicative of a non steady-state solar wind. The A_{He} predicted by *Kasper et al.* [2007, equation 2] is approximately 4% and remains relatively steady (i.e., the proton speed is steady) throughout the event. In contrast, the observed A_{He} value (not shown in Figure 1) has a much greater average value of 6%, peaks at 10%, and is highly variable.

[10] In Figure 2 we focus on the time period from approximately 4.5–9.5 UT on Feb 14th, 1996. In Figure 2a we plot 5-point running averages of the following time series: the proton density (blue), the alpha density (red) and A_{He} (green). We plot the running average, as it smoothes variations of a shorter period ($\sim$8 minutes) than we are interested in here. A clear 30-min periodic number density structure can be identified in the proton time series. In Figure 2b, we detrend the time series with a 50-point running average ($\sim$80 minutes) to identify more clearly the 30-min periodicity of both the alpha (red) and proton (blue) density. In general, the enhancements in the alpha density are anticorrelated with the enhancements in the proton density. Specifically, there is a dominant 30-minute fluctuation in both the proton and alpha density from approximately 4.5–9.5 UT, when the alpha and proton fluctuations are in antiphase. We identify with tick marks the region in which the alphas are in particularly clear antiphase with the 30-min proton density periodicity (6.5–8 UT). During this time the wind has a higher proton density and lower alpha density for 30 minutes; then lower proton density and higher alpha density for 30 minutes; then it returns to the original state of high proton density and low alpha density. Importantly, the empirical relationship between A_{He} and proton speed does not predict a 30-minute

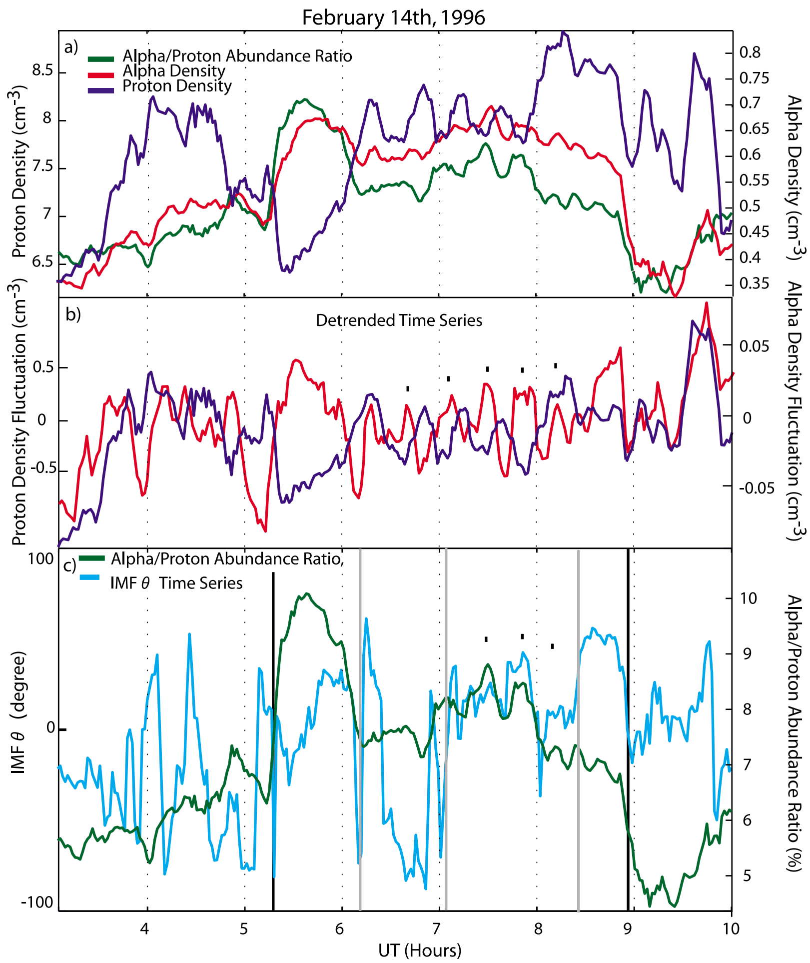

Figure 2. (a) Periodic number density structure seen in the proton density (blue), alpha density (red), and A_{He} (green) time series. (b) Detrended alpha and proton time series. Ticks indicate alpha and proton density periodicity in antiphase. (c) IMF θ (cyan) and A_{He} (green) time series. Vertical lines indicate rotations of interest, and ticks mark periodicity observed in both θ and A_{He}.

periodic variation in A_{He}; on these timescales, some additional process created the A_{He} variations.

[11] In Figure 2c we plot the time series of A_{He} (green) with the IMF θ (cyan). A_{He} varies with the same 30-min periodicity, driven simultaneously by the 30-min periodicity in both the proton and the alpha densities. In this particular event, the θ time series also has variations corresponding to many of the A_{He} variations. There are two large rotations in θ that correspond to discontinuities in A_{He}, occurring just after 5 UT and just before 9 UT (marked with black vertical lines). Between approximately 7 UT and 8.3 UT, θ and A_{He} are correlated and vary with a 30-minute periodicity (marked with ticks). Note that to maintain approximate pressure balance in this periodic density structure, the magnetic field magnitude should be correlated with the alpha density (and A_{He}). In a periodic nature, on a time scale of 30-min, the plasma source region is changing, indicated by A_{He} changes.

[12] Not all features in A_{He} have corresponding θ features, and vice versa. Three large discontinuous rotations in θ occur within the event just after 6 UT, 7 UT, and at 8.5 UT correspond with the middle of the A_{He} depletion (6 UT) or enhancement (7 and 8.5 UT) as opposed to the change in A_{He}; in other words the plasma remains the same across those three rotations (marked with grey vertical lines). The rotations at 6 and 7 UT are both sharp rotations across the sector boundary. The rotation at 7 UT occurs when the 30-min periodicity and antiphase behavior is seen clearest. Importantly, though θ and A_{He} variability are largely correlated, the substantial, discontinuous rotations in θ while A_{He} remains constant are not consistent with the behavior of slow mode waves.

[13] To explore the correlation between A_{He} and the IMF further, we show in Figure 3 a scatterplot of the alpha density measurements (using the original data, as shown in Figure 1) versus the radial component of the IMF from 4.5–9.5 UT. There is a clear trend between the alpha density and the IMF during this event. The observation that the alpha density in this case is smoothly correlated with the magnetic field, even as it switches sign, excludes the possibility that we are observing multiple crossings of a single twisted flux tube or passing through separate but unrelated flux tubes.

[14] Using spectral analysis on the original time series (i.e., not the time series that was averaged or detrended), we confirm the 30-min periodicity identified visually with Figure 2 in the alpha density, proton density and A_{He}. Our spectral analysis technique follows that of *Mann and Lees* [1996], as implemented by *Viall et al.* [2008, 2009]. We use

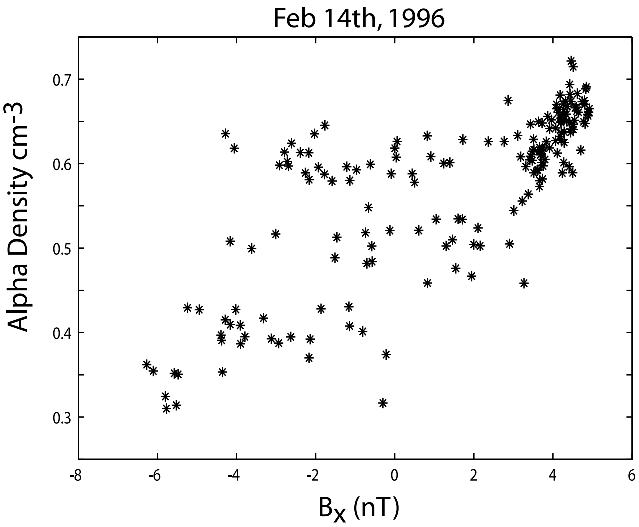

Figure 3. Scatter plot of B_x versus alpha density over the interval 4.5–9.5 UT.

Thomson's [1982] multitaper method to estimate the spectra and show spectral estimates in Figure 4 for all three time series with their respective backgrounds, estimated over 4.5–9.5 UT (the same period of time included in Figure 3). We consider spectral peaks significant only if they pass both an amplitude test as well as a harmonic F-test simultaneously at the 95% confidence threshold. The peaks that pass this rigorous combination of tests in all three time series are the 30-min and 15-min periodicities, indicated with vertical lines. The alpha density varies with two of the same periodicities the proton density exhibits, and is in antiphase. Identifying two periodicities in common between all three time series is further evidence that this event is not a slow mode wave. We argue that solar wind periodic density structures, in at least this instance, were formed somewhere in the corona, frozen into the solar wind, and then convected out to 1 AU.

3. Discussion and Interpretation

[15] For this event, the anticorrelated nature of the periodic proton density structure with the alpha density strongly argues for either time varying or spatially varying coronal source plasma. We discussed the MHD model of *Endeve et al.* [2004] as a possible mechanism to generate periodic proton density structures; the anticorrelated alpha density fluctuations must also be explained. The A_{He} predicted by *Kasper et al.* [2007] equation 2, did not predict the high amplitude, short periodicities (i.e., 30 minutes) observed during this event. However, *Endeve et al.* [2005] may further provide insight. They modeled closed coronal flux tubes that open and release plasma into the solar wind. When the loop is closed, the alphas settle gravitationally such that when the loop is opened, the solar wind is alpha-poor for 10–20 h, after which time the alphas are heated enough to escape with the protons. This process is a possible explanation as to how the solar wind A_{He} could change with time, but does not explain the periodic nature of that change, the multiple periodicities, or the overabundance of alphas, as observed in the event presented here. An accurate theory explaining these periodic density fluctuations will need to address all aspects observed during this event study.

[16] We note that not every instance of periodic density structures exhibit alpha periodicities which are in antiphase. However, in addition to the event explored in this paper, we have reviewed dozens of others, and many of the periodic density structure events do indeed exhibit this behavior. A future longer paper will discuss more events of this unambiguous sort.

[17] Lastly, the observations we have presented here are consistent with recent ideas that there is non-turbulent 'fossil structure' created at the Sun and convected out to 1 AU [*Bruno et al.*, 2001; *Borovsky*, 2008]. Though this study focused more on the particle than the magnetic field structures, there are interesting features of the magnetic field occurring during this event. The atypical magnetic field configuration indicated in Figure 1, the interesting connection between the θ-component of the IMF and A_{He} shown in Figure 2, and the B_x and alpha density correlation shown in Figure 3 all provide evidence of either a time varying coronal composition or different source regions.

4. Summary and Conclusion

[18] We analyzed A_{He} variations during an event containing periodic proton density fluctuations in order to determine whether the periodic density fluctuations developed in the interplanetary medium, or if they were instead more likely generated somewhere within the solar corona. As the proton density fluctuates in a periodic nature, the alpha density also fluctuates at the same periodicity in antiphase with the protons. We demonstrate a trend between the radial component of the interplanetary magnetic field and the alpha density; this is a further possible constraint on

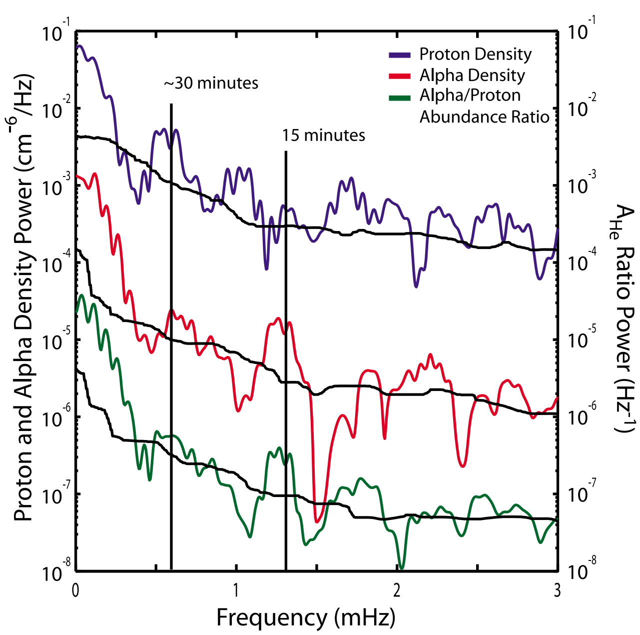

Figure 4. Spectral estimates of proton (blue), alpha (red), and A_{He} (green) time series with their respective background spectra (black). Two periodicities (vertical bar) pass both the narrow band test and the F-test at the 95% confidence threshold simultaneously in all three spectra.

mechanisms for coronal and solar wind variability. We discussed our study in relation to other recent work and contend that the solar wind observed during this event is generated through a time or spatially varying coronal source. The ability to distinguish between local and coronal processes using A_{He} illustrates the importance for these kinds of measurements to be made on Solar Orbiter and Solar Probe. Further event studies are needed and will be presented in a future paper.

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J. Kasper, Harvard-Smithsonian Center for Astrophysics, 60 Garden St. Cambridge, MA 02138, USA.

H. E. Spence and N. M. Viall, Department of Astronomy, Boston University, Boston, MA 02215, USA. (nickiv@bu.edu)