DETECTION OF PLASMA FLUCTUATIONS IN WHITE-LIGHT IMAGES OF THE OUTER SOLAR CORONA: INVESTIGATION OF THE SPATIAL AND TEMPORAL EVOLUTION

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ABSTRACT

This work focuses on the first results from the identification and characterization of periodic plasma density fluctuations in the outer corona, observed in STEREO-A COR1 white-light image time series. A two-dimensional reconstruction of the spatial distribution and temporal evolution of the coronal fluctuation power has been performed over the whole plane of the sky, from 1.4 to 4.0 Rs. The adopted diagnostic tool is based on wavelet transforms. This technique, with respect to the standard Fourier analysis, has the advantage of localizing non-persistent fluctuating features and exploring variations of the relating wavelet power in both space and time. The map of the variance of the coronal brightness clearly outlines intermittent spatially coherent fluctuating features, localized along, or adjacent to, the strongest magnetic field lines. In most cases, they do not correspond to the visible coronal structures in the brightness maps. The results obtained provide a scenario in which the solar corona shows quasi-periodic, non-stationary density variations characterized by a wide range of temporal and spatial scales and strongly confined by the magnetic field topology. In addition, structures fluctuating with larger power are larger in size and evolve more slowly. The characteristic periodicities of the fluctuations are comparable to their lifetimes. This suggests that plasma fluctuations lasting only one or two wave periods and initially characterized by a single dominant periodicity either rapidly decay into a turbulent mixed flow via nonlinear interactions with other plasma modes, or they are damped by thermal conduction. The periodic non-stationary coronal fluctuations outlined by the closed field lines at low and mid latitudes might be associated with the existence of slow standing magneto-acoustic waves excited by the convective supergranular motion. The fluctuating ray-like structures observed along open field lines appear to be linked either to the intermittent nature of the processes underlying the generation of magnetic reconnection in the polar regions or to the oscillatory transverse displacements of the coronal ray itself.

Key words: magnetohydrodynamics (MHD) – methods: data analysis – Sun: corona – Sun: magnetic topology – Sun: oscillations – waves

Online-only material: color figures, animations

1. INTRODUCTION

Magnetohydrodynamic (MHD) oscillations and waves in the coronal plasma are of great interest in solar physics due to the crucial role that these processes might play in coronal heating and solar wind acceleration (e.g., Cranmer et al. 1999; Walsh & Ireland 2003; Ofman 2004). Coronal waves are also important as a probe for MHD coronal seismology (e.g., Uchida 1970; Roberts et al. 1984; Nakariakov & Vrčič 2005): comparison of the observed properties of these phenomena, such as periods, wavelengths, amplitudes, spatial and temporal scales, and time evolution, with theoretical models may cast some light on the physical quantities of the solar corona, such as the magnetic field and the transport coefficients, which are not yet accurately known from an observational point of view.

Periodic and quasi-periodic phenomena in the solar corona were first observed with ground-based radio instrumentation in the 1980s (Aschwanden 1987). The launch of the Solar and Heliospheric Observatory (SOHO; Domingo et al. 1995) in 1995 and the Transition Region and Coronal Explorer (TRACE; Handy et al. 1999) in 1998 opened a new era in the investigation of coronal waves and transients. The highly improved spatial and temporal resolution of the new instruments carried by these spacecrafts allowed the identification, almost ubiquitously in the corona, of a large variety of MHD waves such as standing fast kink disturbances, fast sausage and slow longitudinal acoustic modes, propagating slow and fast waves, and so on. They permeate individual structures of the inner corona, such as loops, polar plumes, and helmet streamers, with different spatial and temporal scales and periods ranging from a few seconds to several minutes. Longer period (8–27 hr) oscillations have been observed with the Extreme ultraviolet Imaging Telescope/ SOHO (Delaboudinière et al. 1995) in the inner corona in a large-scale EUV filament (Foullon et al. 2004). The Ultraviolet Coronagraph Spectrometer/ SOHO (Kohl et al. 1995) has allowed us to discover density fluctuations in the outer corona, in the region where the solar wind is accelerated. Slow magneto-acoustic waves with periods of a few minutes (6–10 minutes) have been detected in a coronal hole between 1.5 Rs and 2.1 Rs by Ofman et al. (2000) and Morgan et al. (2004). Large-scale density fluctuations with longer periods (from a few hours to a few days) have been discovered in both the fast wind at high latitude at 2.1 Rs by Ofman et al. (2000) and Morgan et al. (2004).
scales of periodic and quasi-periodic variability have been detected, and information on their temporal evolution is in general still lacking. Moreover, due to the limited instantaneous field of view (FOV) of the spectrometers used in the previous studies, only a small fraction of the plane of the sky (POS) has been investigated at any given time. This has not allowed us to derive the spatial distribution of the plasma fluctuations.

The aim of this paper is to overcome these major limitations on the study of the periodic and quasi-periodic variability of the outer corona by exploiting the improved observational capabilities of \textit{STEREO}-A COR1 (Thompson et al. 2003; Howard et al. 2008; Kaiser et al. 2008), launched in 2006, and by adopting a diagnostic technique that is able to provide both spatial and temporal information on coronal plasma fluctuations. This is achieved by analyzing the long-term time series of the total brightness derived from the high-cadence white-light images obtained with COR1 and by adopting the wavelet transforms as an analysis technique, which allows us to separate spatial and temporal variations. The detailed study of the spatiotemporal evolution of the non-stationary plasma fluctuations, observed at different timescales, allows a two-dimensional reconstruction of the wavelet power which maps the outer corona from 1.4 to 4.0 \( R_\odot \) in a systematic manner and over a time interval of nine days. This approach allows us to investigate the correlation between coronal periodic and quasi-periodic phenomena and magnetic structures and to attempt an identification of the origin, excitation, and dissipation mechanisms of the detected variability.

The layout of this paper is as follows. A description of the observations is given in Section 2. Section 3 provides a description of the analysis of the data and a presentation of the results. Discussion, interpretation of the results, and conclusions are given in Sections 4, 5, and 6, respectively. The Appendix reports on the methodological details of the wavelet technique.

2. OBSERVATIONS

The present analysis is based on white-light images of the outer solar corona obtained during the minimum of solar activity in 2008 with the coronagraph COR1-A, which is part of the SECCHI (Sun–Earth Connection Coronal and Heliospheric Investigation) instrument suite on board the “ahead” spacecraft of the twin \textit{Solar Terrestrial RElations Observatory} (\textit{STEREO}) satellites. COR1-A observes the solar corona from 1.4 to 4.0 \( R_\odot \), providing 1024 \times 1024 pixel images with a spatial resolution of 7.5′, or \( 0.008 \, R_\odot \) per pixel.

The entire set of observations consists of \( N = 2592 \) exposures acquired with a cadence of 5 minutes in the 9 day intervals between 2008 April 14 at 00:05 UT and 2008 April 22 at 23:55 UT. During the selected observational run, the Sun was in an extremely quiet period with very few sunspots, small active regions, and no evidence of eruptive phenomena.

Continuous temporal series of white-light total brightness are derived for each pixel of the COR1-A images by using the IDL routine \texttt{SECCHI\_PREP} in the SolarSoft library. This routine also allows the calibration of the data and the subtraction of the background. The total brightness is computed in mean solar brightness \( B_\odot \) units by combining the intensity radiation \( I \) of a rapid polarization sequence triplet measured at polarizer positions 0°, 120°, and 240°: \( B = 2/3(I_0 + I_{120} + I_{240}) \) (Billings 1966). As an example, Figure 1 shows the total brightness of the solar corona on 2008 April 18 at 21:50 UT; the \textit{SOHO}/Michelson Doppler Imager (MDI; Scherrer et al. 1995) magnetogram (as seen from the \textit{STEREO}-A satellite on 2008 April 19 at 00:04 UT) is superimposed on the white-light image. In the same figure, the magnetic configuration of the corona is outlined by extrapolating the coronal magnetic field lines according to the model developed by Schrijver & DeRosa (2003; employed in the SolarSoft package called the Potential Field Source Surface (PFSS)). This model is based on the evolving full-Sun Carrington maps of the photospheric magnetic field measured by the \textit{SOHO}/MDI instrument. The coronal magnetic field is extrapolated from the photospheric field via the PFSS approximation, in which the field is assumed potential in the coronal volume between the photosphere and a spherical source surface located at a height of 2.5 \( R_\odot \). Since the coronal field models are provided at a 6 hr cadence by the online database of PFSS, Figure 1 shows the magnetic configuration closest in time to the total brightness frame of 2008 April 18 at 21:50 UT. The extrapolations have been generated while taking into account the instantaneous line of sight of \textit{STEREO}-A by considering the Carrington latitude and longitude values at each time.

3. ANALYSIS AND RESULTS

In this paper, we adopt the wavelet analysis with the aim of identifying periodic and quasi-periodic density fluctuations over the whole outer solar corona and exploring their fine spatial structure and temporal evolution at different timescales. In recent years, this technique, applied to observations of the inner corona, led to the detection of periodic phenomena such as (1) outward propagating oscillations in an active region bright loop with periods of 3–7 minutes (De Moortel et al. 2000), (2) sporadic oscillations with periods of 7–8 minutes in the quiet corona (Morgan et al. 2004), and (3) coherent fluctuations in a weak magnetic network region (Bloomfield et al. 2004).

The wavelet analysis is in fact a powerful tool for analyzing non-stationary time series or time series with expected localized variations of power. By decomposing a time series into the time-frequency space, it is possible to determine both the dominant frequencies/periodicities of the variability and the related power modulation in time (Torrence & Compo 1998). The main benefit of the wavelet over the Fourier analysis resides in its capability of identifying the periodic components of non-stationary signals. By combining the results obtained at multiple locations, the spatial distribution and temporal variability of a given data set can be reconstructed. Details on the wavelet formalism and methodology, with particular attention to its application to the present analysis, are reported in the Appendix.

We applied the wavelet transform to the nine day time series of the total brightness derived for each pixel of the COR1-A images. The trends affecting the temporal series in this interval were removed previously; the effect of the solar rotation is filtered out by applying a Fourier highpass band filter with a cutoff frequency of \( 2.8 \times 10^{-3} \) Hz, taking into account the coronal rotation rate derived by Giordano & Mancuso (2008). The long uninterrupted time series and the short temporal sampling, 5 minutes, allow the detection of periodicities ranging from 10 minutes (the Nyquist–Shannon period) up to 10 hr, the cutoff timescale of the highpass filter.

Since the Sun was very quiet during the observational interval, without any evidence of eruptive or transient phenomena, the data are smoothly varying without abrupt jumps or sharp peaks. As an example, the left panel of Figure 2(a) shows the total brightness measured at 2.05 \( R_\odot \) and 212° counterclockwise from the North pole (which refers to a ray-like structure;
Figure 1. Total brightness of the outer solar corona, from 1.4 to 4.0 \( R_\odot \), derived from the COR1-A observations obtained on 2008 April 18 at 21:50 UT. The extrapolated magnetic field lines and the SOHO/MDI disk magnetogram, obtained on 2008 April 19 at 00:04 UT as seen from STEREO-A, are also shown. The white dashed line indicates the edge of the STEREO occulter.

(An animation and a color version of this figure are available in the online journal.)

see Section 3.1) before (black curve) and after (red curve) the filtering process. The right panel of Figure 2(a) shows the result of a Gaussian smoothing of the red curve which acts as a lowpass filter for a period smaller than 2.5 hr and allows us to cast a preliminary rough glance at the total brightness variability behavior. Highly unstable fluctuations whose amplitudes vary even significantly with time (strong impulses alternate with phases of damped amplitude) are present all along the observational run. This behavior is noted in arch-shaped structures as well (see Section 3.1). Figure 2(b) shows the wavelet power spectrum derived from the filtered brightness time series, reported as a red curve in the left panel of Figure 2(a), by using the Paul mother wavelet (see the Appendix). The ordinate is the Fourier period \( \tau \), corresponding to the scale \( s \) of the wavelet, and the abscissa is the time of observation. The contour plot indicates the power of the total brightness fluctuations derived by means of the wavelet transforms, which is the variance of the total brightness time series detected by STEREO-A COR1. The cross-hatched area below the cone of influence (COI) line (continuous line in Figure 2(b)) is the region of the wavelet spectrum where edge effects, due to the finite length of the time series, are significant. The shorter periodicities found above the COI line are due to the non-stationary periodic signals present in the data. The thick dashed contours delimit regions where the wavelet power is significant; that is, they identify real periodic signals at a confidence level of 99\%, as determined via a 2 degree of freedom \( \chi^2 \) distribution (see Torrence & Compo 1998 and references therein, as well as the Appendix).

As shown in Figure 2(b), most of the power is concentrated in the 4–8 hr periodicity range. In this band, its value exhibits significant changes, with a peak on 2008 April 20 at about 12:00 UT. As expected, negligible power is found at periods larger than 10 hr, where frequency contributions have been filtered out. Hence, we are confident that the high-power features identified during the observational run are not to be ascribed, for instance, to the passage of coronal features across the instantaneous FOV during solar rotation.

A vertical slice through the wavelet plot of Figure 2(b) is a measure of the spectrum at a given instant. The average of the local wavelet power spectra over the observational interval gives the global wavelet spectrum (as defined in Equation (A4)) shown in Figure 2(c). It is worth noting that the global wavelet spectrum approaches the results that can be obtained with the Fourier spectrum of the time series (Percival 1995). The global spectrum is above the 99\% confidence level (red dotted line...
Figure 2. (a) Left: coronal total brightness detected on 2008 April 18 at 2.05 R⊙ and 212° counterclockwise from the North pole (black curve); the red curve has been obtained by filtering out any trend, including the trend due to solar rotation, from the original time series (black curve). (a) right: Gaussian smoothing of the filtered time series (red curve on the left panel) which acts as a lowpass filter for periods smaller than 2.5 hr; note the finer scale resolution of the ordinate axis. (b) Wavelet power spectrum of the filtered time series using the Paul wavelet function; the ordinate is the Fourier period $\tau$ in hr; the abscissa is the time of observation; the continuous line is the cone of influence (COI) and delimits a cross-hatched area where the power spectrum is not significant, while the thick dashed contours delimit areas where the wavelet power is significant with a 99% statistical confidence, for a white-noise process. (c) Wavelet power spectrum averaged over the entire observational interval for the data set reported in (a) (i.e., global wavelet spectrum); the red dashed line is the 99% statistical confidence for a white-noise process. (d) Averages of the wavelet power over the 0.5–1 hr, 1–2 hr, 2–4 hr, and 4–8 hr periodicity bands (from top to bottom, respectively); the red dashed lines are the corresponding 99% confidence levels. (A color version of this figure is available in the online journal.)
This quantity is a measure of the average variance of the total brightness as a function of time. The total brightness power exhibits significant modulations with timescales that are of the same order as the periodicities considered: the primary peaks in each band are one or two periods wide. Moreover, the longer the periods considered, the slower the temporal evolution of the total brightness variance (Figure 2(d)). We will discuss a possible physical interpretation of this temporally intermittent behavior in Sections 4 and 5.

Since the results of the wavelet analysis are strongly dependent on the choice of the wavelet function (see the Appendix), the present results (Figure 2(b)) are compared with those derived using the Morlet wavelet (Figure 3(b)). The same features appear to be significant in both wavelet power spectra at approximately the same time-periodicity locations and with comparable power. However, since the Paul mother wavelet is more sharply defined in time than the Morlet function (Figure 7), the peaks in the power spectrum shown in Figure 2(b) are sharper in the time direction than those derived in Figure 3(b), thus indicating a better time resolution in the case of the Paul wavelet function. On the other hand, since the Morlet mother wavelet is narrower in the periodicity space than...
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Figure 4. Two-dimensional maps of the total brightness fluctuation power averaged over the 0.5–1 hr, 1–2 hr, 2–4 hr, and 4–8 hr periodicity bands, respectively, obtained in the FOV of COR1-A on 2008 April 18 at 21:50 UT. The extrapolated magnetic field lines and the SOHO/MDI disk magnetogram, as seen from STEREO-A on 2008 April 19 at 00:04 UT, are also shown. The plotted average variance of the total brightness is significantly above the 99% confidence for the assumed white noise. The dashed white line indicates the edge of the STEREO occulter.

(Animations and a color version of this figure are available in the online journal.)

the Paul function (Figure 7), the same peaks appear less elongated and better defined in the period direction, thus indicating that a better frequency resolution is obtained if the Morlet function is applied (Figures 3(b) and 2(b)).

The wavelet transforms based on the Paul mother wavelet (characterized by few zero crossings; Figure 7) can, in principle, identify many types of signatures in the power spectrum, such as sharp variations in the input data like simple rounded impulses, and not just waves. Nevertheless, by taking into account that the same significant high-power features are found in both the Paul and Morlet analyses and that the Morlet function is more suitable for detecting signatures of periodic and quasi-periodic fluctuations (since it contains more “waves” than the Paul function; Figure 7), it is possible to infer that the signals detected by COR1-A might not be simply variable.

Thus, since the main aim of this study is to localize in time and space any quasi-periodic feature associated with expected non-stationary processes, the Paul mother wavelet, which assures a better time localization than the Morlet function, has been used throughout the analysis reported hereafter.

In summary, Figures 2(b), (c), and (d) show that significant non-stationary variability exists over a broad range of periodicities, extending from 0.5 up to 8 hr; the strongest fluctuations are found in the 4–8 hr band. The observed variability persists throughout the observational interval. The temporal evolution of the wavelet power is strictly related to the periodicities involved: longer periodicities are characterized by a more slowly evolving wavelet power.

3.1. Two-dimensional Reconstruction of the Wavelet Power

The spatial and temporal evolution of the total brightness fluctuation power is obtained by computing the averages (Equation (A5)) as functions of time, pixel by pixel, for the four selected periodicity bands. The results have been used to construct four different movies (available as online material in

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Figure 5. Left: wavelet power averaged over the 4–8 hr periodicity band, inferred in the western hemisphere of the COR1-A FOV on 2008 April 19 at 09:35 UT. The dots outline an arch-shaped fluctuating structure. The continuous white line indicates the solar disk limb, while the dashed one indicates the edge of the STEREO occulter. Top right: three-dimensional histogram showing the spatial profiles of the variability amplitude relative to the instantaneous total brightness referring to different points along the arch at different times (one every about 2 hr) from 2008 April 18 at 16:35 UT to 2008 April 19 at 17:35 UT. Middle right: three-dimensional histogram showing the temporal profiles of the power of the fluctuations inferred along the arch, in the same time interval as in the top right panel. Bottom right: time instants when the wavelet power of the different temporal profiles reaches its maximum as a function of the curvilinear coordinate along the arch-shaped structure. The linear fit is shown as a dotted line.

The features corresponding to power enhancements are often but not always localized along the magnetic field lines (Figure 4). Moreover, they do not correspond to bright resolved structures with sharp edges in the total brightness images of the solar corona. The power of the bright features, shown in Figure 4, is about 10 times greater than that of the dimmer regions (Figure 2(d)). For instance, the power associated with the bright polar rays evident in the 4–8 hr band is about $2-4 \times 10^{-23} (\delta B / B_{\odot})^2$, while that of the dim regions between bright rays is $1-2 \times 10^{-24} (\delta B / B_{\odot})^2$. Similar ratios are found for the wavelet power in the bright equatorial arches compared to those derived for the dark cavities. The periods of the embedded fluctuations are related to the thickness ($d_\perp$) and the length ($L$) of the arch-shaped and ray-like features, determining the spatial scales of the fluctuating structures; that is, periodicities are longer for larger spatial scales. As an example, in the 4–8 hr band, the thickness of the fluctuating structures is $d_\perp \sim 0.01 R_{\odot} = 7 \text{ Mm}$, while the extrapolated lengths (down to the solar disk) are $L \sim 2.9 R_{\odot} = 2.03 \times 10^3 \text{ Mm}$ and $L \sim 1.4 R_{\odot} = 980 \text{ Mm}$ for the arches and rays, respectively.

3.2. Spatial and Temporal Profiles of the Fluctuation Power

In order to investigate in detail how the power varies and evolves along the bright non-stationary fluctuating features, spatial and temporal profiles of the power of the total brightness are derived as a function of a linear coordinate along arches and rays (Figure 4). Since these structures are more evident for periods of 4–8 hr, hereafter we focus our attention on this periodicity band.

The left panel of Figure 5 shows the power averaged over the 4–8 hr band, in the western hemisphere of the COR1-A FOV on
2008 April 19 at 09:35 UT. There is clear evidence for a system of two encapsulated closed arches, protruding from the occulted coronal region, i.e., from 1.4 \( R_\odot \) up to about 1.7 \( R_\odot \) and 2.0 \( R_\odot \), respectively. The arches are separated by a dark cavity. The dots outline the outer arch.

The spatial profiles of the fluctuation amplitude along the outer arch are plotted as a three-dimensional histogram in the top right panel of Figure 5. The \( x \)-axis represents the curvilinear coordinate defined as the incremental distance along the path from the southernmost visible part of the arch. The \( y \)-axis represents the time (in hours) starting on 2008 April 18 at 16:35 UT. The spatial behavior of the total brightness fluctuations along the arch is measured at each point by the percentage variation of their amplitude relative to the instantaneous total brightness (\( z \)-axis). Spatial profiles (along the \( x \)-axis) are obtained at a cadence of 2 hr in the period from 2008 April 18 at 16:35 UT to 2008 April 19 at 17:35 UT. The relative amplitude of the total brightness fluctuations increases along the arch, reaching its maximum of about 3\% around the cusp of the closed structure, a factor of \( \sim 2 \) higher than at the base. The trend of the spatial profiles is quasi-independent of the time.

The temporal profiles of the fluctuation power inferred at each point along the arch are plotted as a three-dimensional histogram in the middle right panel of the same figure. The time interval over which the temporal profiles have been derived is much longer (more than 24 hr) than the lifetime of the fluctuating feature, thus ensuring that its entire temporal evolution is indeed monitored. The \( x \)-axis represents the time (in hours) starting on 2008 April 18 at 16:35 UT. The \( y \)-axis represents the curvilinear coordinate along the arch. The \( z \)-axis is the normalized wavelet power for each temporal profile. The total brightness fluctuations along the arch are typically characterized by a monotonic damping. This suggests that the fluctuating structures found in the corona are non-stationary in nature. The 1/e width of the main fluctuation at each point of the arch provides information about the lifetime of the fluctuating structure, which is slightly less than 10 hr, that is, on the same order as the temporal scales examined in the band of 4–8 hr. The power reaches its maximum on 2008 April 19 at about 07:35 UT almost simultaneously along the arch, except at the northernmost base where the maximum is reached slightly earlier. This fact could be due to a tilt of the fluctuating arch relative to the POS, which would produce a variable column depth along the line of sight, thus modulating the temporal profiles of the wavelet power along the structure.

The bottom panel of Figure 5 shows the temporal and spatial coordinates of the power peak in the oscillating arch. The error bars are derived from the 1/e width of the corresponding temporal profiles. The linear coefficient of the fit shown as a dotted line, \( B = 2.40 \pm 3.01 \text{ hr} R_\odot^{-1} \), is consistent, within the uncertainties, with a flat curve. This implies that the total brightness fluctuation detected reaches its maximum power fairly simultaneously along the arch, and hence the fluctuations are coherent in phase.

The same analysis has also been performed on a ray-like structure in the southwestern hemisphere, shown in the left panel of Figure 6, which shows the wavelet power averaged over the 4–8 hr band on 2008 April 20 at 13:35 UT. The spatial and temporal profiles of the wavelet power of the total brightness along the ray are shown as three-dimensional histograms on the top and middle right panels of the figure. They are very similar to those obtained for the arch-like structure and can be summarized as follows: (1) the fluctuations strengthen with distance along the ray: within 1 \( R_\odot \), their amplitude, relative to the total brightness, increases by a factor of two up to 3%; farther out, the structure is no longer observed; (2) the fluctuations are non-stationary and damped with a lifetime of about 10 hr; the lifetime of the structure is of the same order of the periodicities of the embedded fluctuations, that is, slightly less than 10 hr; (3) the fluctuations along the ray-like structure are coherent in phase.

4. DISCUSSION

Strong non-stationary fluctuating structures have been detected in the solar corona as closed arches in the equatorial regions and ray-like features in the polar holes. They are often found corresponding with the strongest lines of the coronal magnetic field, as shown in Figure 4. The observed variability can be ascribed to variations in the electron density of the emitting coronal plasma, since the white-light emission in the corona is due to the Thomson scattering of the solar disk photons by the free electrons. The periodicities observed in the fluctuating corona cover a wide range of scales, from 0.5 to 8 hr; the strongest signals are found in the 4–8 hr band, where the fluctuating structures have a characteristic transverse and longitudinal spatial scale of \( \sim 0.01 R_\odot = 7 \text{ Mm} \) and \( \sim 1.4–2.9 R_\odot = 980–2030 \text{ Mm} \), for the ray and arch features, respectively. These results confirm the findings of the first studies on density fluctuations in the outer solar corona by Bemporad et al. (2008) and Telloni et al. (2009a, 2009b). In these papers, quasi-periodic oscillations with periodicities larger than a few hours were found in the Fourier power spectra; however, the analyses were much more limited in space and time since they were performed with data obtained with a spectrometer.

Notwithstanding the fact that we have ascertained that the total brightness variability is non-stationary in nature, it reveals a long-term persistence throughout the observational time interval of nine days. This fact suggests that a non-transient, persistent mechanism of quasi-periodic nature, not necessarily acting at the coronal level, continuously drives density fluctuations in the solar corona. The fluctuations continuously originate and successively decay in a time that is of the same order as their characteristic temporal scales; this causes a modulation of the variance of the total brightness as seen in Figures 2(a) and (d) and in the maps of the corona of Figure 4. Such behavior is clearly evident in the movies of the spatiotemporal evolution of the wavelet power (available in the electronic version of this paper). It can be suggested that the density fluctuations, which are initially distinct and characterized by a single dominant periodicity, either rapidly decay into a turbulent mixed flow via nonlinear interactions with other plasma modes or are damped by thermal conduction.

Furthermore, the results obtained in this study point to a tight correlation between the temporal evolution of the power of the plasma variability detected in this work and the spatial and temporal scales of the fluctuating coronal features. Longer periodicities are indeed typical of fluctuating structures that are of larger size and are evolving more slowly. This reflects an overall characteristic of the Sun: larger scale solar structures have characteristic timescales longer than those corresponding to smaller scale structures. For instance, the strong correlation existing between the size and the time duration of the polar plumes (Llebaria et al. 2002) is well known. This behavior is also evident in the movies (available in the electronic version of this paper) that show the spatial and temporal evolution of the magnetic features, both arches and rays, in the corona from 1.4 to 4.0 \( R_\odot \).
Finally, the analysis of the temporal evolution of the wavelet power along the non-stationary arch-shaped and ray-like structures (Section 3.2) reveals that the plasma fluctuations are highly coherent, since each point along the coronal magnetic structure fluctuates with the same phase. The phase coherence of the plasma fluctuations might indicate that they are likely to be generated simultaneously by the same driver mechanism.

4.1. Assessment of Solar Rotation Effects

Even if the frequency contribution due to the solar rotation has been filtered out, in order to ensure that the same volume of the corona is analyzed (as described in Section 3), it cannot be a priori excluded that in observations performed at the limb, tangential discontinuities separating adjacent radial structures with different electron density (for instance, magnetic flux tubes co-rotating with the Sun) could mimic wave phenomena. During limb observations of the quiet corona, the maximum density along the line of sight is at the POS, due to its proximity to the disk. Thus, a density variation caused by quasi-regularly spaced tangential discontinuities, due to the rotation of the Sun, induces a quasi-periodic signal in the coronal emission detectable at best when crossing the POS. We have tested this occurrence by evaluating the temporal scale of rotating long-lived structures, \( \tau_r = d_{\perp}(T_r/(2\pi r)) \), where \( d_{\perp} \) is the geometric thickness of the oscillating arch, perpendicular to the magnetic field lines, \( T_r \sim 27.5 \, d \) is the rotation period observed in the outer corona (Giordano & Mancuso 2008), and \( r \sim 1.5 \, R_\odot \) is the average heliocentric distance of the fluctuating coronal arch. By assuming \( d_{\perp} \sim 0.01 \, R_\odot \), which is the measured value in the 4–8 hr periodicity band, we obtain \( \tau_r \lesssim 1 \, h \), which is significantly smaller than the periodicities characterizing the fluctuating arch. We have also addressed this issue by assessing the effect of rotation on the temporal evolution of a coronal magnetic loop, formed by numerous spatially unresolved filamentary sub-structures (Klimchuk 2009). The loop fine structure has been modeled by considering a curved cylinder of longitudinal and transverse dimensions of \( 2.9 \, R_\odot \) and \( 0.01 \, R_\odot \), respectively (dimensions consistent with the length, \( L \), and the thickness, \( d_{\perp} \), of the observed arch-shaped structure), consisting of many sub-elements characterized by different densities. Based on this model, we compute the coronal electron density as a function of time at the POS in a time interval of about one day. In the hypothesis that the randomly distributed sub-structures produce a correlated signal, the Fourier analysis of the synthetic coronal emission shows that the dominant mode of variability is consistent with the crossing timescale of the rotating arcade-system, i.e., \( \sim 1 \, h \), while significantly less power is found at longer periods.

The effect of solar rotation should be negligible in the case of polar structures that develop at high latitudes (Wilhelm et al. 2011). For instance, the shape of the plumes on spatial scales of \( \approx 30 \) arcsec is nearly invariant for hours to days (Waldmeier 1955). Llebaria et al. (2002, 2011) describe polar plumes as enduring structures showing brightness variations that might be ascribed to solar rotation at timescales longer than about...
The intrinsic variations of the plume brightness on scales of the order of 6 h, probably due to the intermittent nature of the generating process, are superimposed on this long-term variability. Therefore, in the 4–8 hr band, where, in a plume-like feature, we find significant variability, the effect of solar rotation should be negligible.

Before concluding that the arch-shaped power enhancements can be interpreted as being due to intrinsic coronal density fluctuations or even more MHD waves, we also have to rule out another effect that could, in principle, mimic power in the wavelet maps, i.e., any possible spatial motion of an arch-shaped structure with clear edges. Quasi-periodic spatial displacements of coronal loops, detected by TRACE in the inner corona, have been reported in many papers (e.g., Aschwanden et al. 1999). They are commonly triggered by nearby flare events and are typically kink instabilities characterized by timescales of the order of a few minutes. Note, in this respect, that no flares or eruptive phenomena were detected during the examined observing run and, moreover, that the fluctuations found in this study are characterized by much longer timescales. Finally, power due to non-intrinsic variability, such as that generated by a simple pulse of material injected in the arch with a duration appropriate to trigger the timescales of the detected fluctuations, can also be ruled out on the basis of the high coherence of the signal found all over the characteristic fluctuation lifetimes.

The analysis shows that the non-stationary density fluctuations outlining closed and open coronal structures, such as arch systems and ray-like features, can be ascribed to intrinsic brightness variations with possible MHD wave character. The compressive components of MHD waves can indeed perturb the ambient solar corona, periodically or quasi-periodically modulate the electron density, and, in the end, generate plasma fluctuations, which can be observed by a white-light imaging coronagraph such as STEREO-A COR1.

5. INTERPRETATION

5.1. Arch-shaped Structure Fluctuations

Theoretically, various MHD waves are predicted in coronal loops. The dispersion relation for magneto-acoustic waves (e.g., Priest 1987) is satisfied by two kinds of waves: a slow-mode branch, with acoustic phase speeds, and a fast-mode branch with Alfvén speeds. The class of the fast magneto-acoustic waves includes a symmetric sausage mode and an asymmetric kink mode. In the sausage mode, opposite sides of an arcade oscillate in anti-phase and the central axis remains undisturbed, while in the kink mode, the opposite sides and the central axis oscillate in phase. However, both modes drive plasma fluctuations along the arcade characterized by the same phase as those observed in the coronal arch and detected in the present analysis (Figure 5). Hence, these MHD modes, as well as slow-mode waves, can be considered physical candidates for the interpretation of the observed variability.

5.1.1. Fast-mode Waves

Kink modes produce transverse amplitude oscillations. Oscillatory transverse displacements of coronal loops have been observed in the inner corona in EUV wavelengths with TRACE (e.g., Aschwanden et al. 1999, 2002; Nakariakov et al. 1999; Schrijver et al. 1999, 2002). In the hypothesis that a standing
kink mode is responsible for the observed electron density fluctuations, the characteristic period \( P_{\text{kink}} \) of such a mode at the fundamental harmonic can be derived, according to Aschwanden (2004), as

\[ P_{\text{kink}} \approx \left( 2L/c_x \right) \lesssim \left( 2L/v_A \right), \]

where \( c_x \) and \( v_A \) are the kink and the Alfvén speed, respectively. In low-\( \beta \) plasma conditions, where the thermal pressure is much smaller than the magnetic pressure, \( c_x \gtrsim v_A \), with \( v_A \approx 1000 \text{ km s}^{-1} \), for typical electron densities and magnetic fields in the coronal region of interest. For the observed arch with a measured length of \( L \approx 2.03 \times 10^3 \text{ Mm} \), the characteristic period is \( P_{\text{kink}} \approx 1 \text{ hr} \).

Hence, if the fluctuations detected in the coronal arch were due to standing kink waves, then we would expect kink-mode periods, and in turn electron density fluctuations, of less than 1 hr. It turns out that according to the analysis, the observed variability cannot be ascribed to a standing wave in the kink mode with fixed nodes at the footpoints.

Sausage MHD modes can be excluded as well because they are expected to be completely suppressed at small wavenumbers. In a coronal arch with length and cross section of the order of the observed ones \( (L \approx 2.03 \times 10^3 \text{ Mm} \text{ and } d_x \approx 0.01 R_{\odot}) \), the dimensionless wavenumber is of the order of 0.005, much smaller than the cutoff wavenumber for typical coronal conditions, which falls into the range 0.8–2.4 (Aschwanden 2004).

As a consequence, the sausage-type waves cannot explain the density fluctuations observed in the arch-shaped structure.

### 5.1.2. Slow-mode Waves

Slow-mode oscillations in coronal loops have been imaged for the first time in the inner corona with the Solar Ultraviolet Measurement of Emitted Radiation (SUMER; Wilhelm et al. 1995) spectrometer on SOHO, by measuring the Doppler shift and intensity variations of EUV lines (e.g., Wang et al. 2002, 2003a, 2003b). Slow-mode acoustic waves are essentially compressional, longitudinal sound waves. In coronal conditions, for typical temperatures of \( T \sim 1.5 \text{ MK} \), the sound speed \( c_s \approx 180 \text{ km s}^{-1} \) is generally much smaller than the Alfvén speed \( (v_A \approx 1000 \text{ km s}^{-1}) \), which is \( c_s/v_A \approx 0.2 \). Thus, the phase speed of slow magneto-acoustic waves in coronal loops, namely, the tube speed \( c_T \),

\[ c_T = \frac{c_s v_A}{\sqrt{c_s^2 + v_A^2}} \approx c_s \quad \text{for } c_s \ll v_A, \]

is close to the sound speed \( c_s \) (e.g., Priest 1987).

The period of an MHD slow-mode standing wave, with the two endpoints of a magnetic flux tube as fixed nodes, is the sound travel time of the fundamental harmonic back and forth in the coronal loop, \( P_{\text{slow}} = 2L/c_T \approx 2L/c_s \). Hence, the period of a slow magneto-acoustic standing wave, \( P_{\text{slow}} \approx 6 \text{ hr} \), supported by the observed fluctuating arch structure falls in the 4–8 hr band where most of the power of the detected fluctuations is observed; thus, the fluctuation of the magnetic arch extending in the outer corona out to approximately 2 \( R_{\odot} \) is consistent with a slow magneto-acoustic standing wave. Therefore, the MHD slow-mode standing waves are ideal candidates for the interpretation of the plasma fluctuations embedded in the coronal arch detected in the equatorial region of the quiet corona.

As far as the origin of the slow-mode wave is concerned, one possibility is that the variability is triggered by a pressure disturbance localized near one of the footpoints, which propagates as a slow-mode magneto-acoustic wave in the longitudinal direction along the arch and is reflected at the opposite footpoint, thus generating a standing wave (a compression back and forth along the magnetic flux tube). A stochastic excitation by convective supergranular motions generates slow magneto-acoustic waves with a period that is consistent with those observed in the coronal fluctuating arch. The lifetimes of supergranular cells \( \tau_s \) range from 6 to 20 hr (Aigrain et al. 2004); this interval partially overlaps with the 4–8 hr band, where closed magnetic arches clearly exhibit the largest wavelet power. Further support for this interpretation is given by the value estimated for the wavelengths of slow-mode standing waves triggered by supergranulation, \( \lambda_s = c_T \tau_s \approx c_s \tau_s \approx 5.6 R_{\odot} = 3.89 \times 10^7 \text{ Mm} \). This wavelength is approximately twice the loop length \( L \) of the fluctuating coronal arch, hence it is consistent with a standing wave with fixed nodes at the footpoints of the magnetic flux tube. The present discussion suggests that supergranular convective motions very likely play a crucial role in the excitation of the slow MHD standing waves trapped in the large closed fluctuating magnetic structures extending in the outer corona.

The length of the arch studied in this analysis is compatible with a spatial scale that can trap the standing wave, thus acting as a filter of standing waves with the appropriate wavenumber.

The suggestion that the driver of the standing waves along coronal arches can be identified with the supergranular convective motions is consistent with the results by Telloni et al. (2009a), where the characteristics of the coronal density fluctuations observed at 1.7 \( R_{\odot} \) in low-latitude regions, such as the temporal and spatial scales, the degree of persistence, and phase coherence, were all indicating a likely correlation between the variability of the solar corona and the photospheric dynamics induced by supergranular convection. However, Telloni et al. (2009a) interpret the correlation between the dynamics of supergranulation and the coronal variability by assuming that structures of the supergranulation at the lower levels of the solar atmosphere are maintained in the outer corona; thus, coronal structures crossing the POS during rotation produce a periodic signal whose characteristics depend on the temporal and spatial scales of the supergranulation. In this study, the link to convective motions is different, since, according to the interpretation of the present results, the stochastic motion of the supergranular cells acts as a driver for the excitation of slow magneto-acoustic waves, which remain trapped in the arch structure as standing waves when their wavelengths are compatible with the loop length.

### 5.1.3. Damping of MHD Modes

The MHD slow-mode standing waves, inferred from the density fluctuations of the arch observed in the quiet corona, show a strong damping effect, which has a decay time of the order of the fluctuation period, as shown in the middle right panel of Figure 5. This rapid damping can be ascribed to processes such as thermal conduction, radiative losses, and phase mixing. Thermal conduction and radiative losses are the major nonadiabatic cooling effects, which can contribute to the damping of the wave motion. For typical coronal electron densities \( (n_e \sim 1.2 \times 10^7 \text{ cm}^{-3}) \) and temperatures \( (T = 1.5 \text{ MK}) \), at the average heliocentric distance \( (r \sim 1.5 \text{ } R_{\odot}) \) of a fluctuating arch of length \( L \approx 2.03 \times 10^3 \text{ Mm} \), the cooling time due to thermal conduction from the corona to the chromosphere is of the order of \( \tau_{\text{cond}} \approx 5–6 \text{ hr} \) (Priest 1987). Therefore, thermal conduction can be considered to be an important factor in damping standing slow magneto-acoustic waves trapped in the closed fluctuating coronal arch of Figure 5, since the conductive cooling time is of the same order as the wave damping time, 4–8 hr. The interpretation of thermal conduction as the main
physical mechanism responsible for damping standing slow magneto-acoustic waves in magnetic loops is also supported by the MHD simulations performed by Ofman & Wang (2002) in order to interpret SUMER observations. Meanwhile, since the radiative cooling time, defined by the ratio of the thermal energy and the radiative cooling rate, is generally lower than 1 hr (Priest 1987), radiative losses are negligible in damping the radiative cooling time, defined by the ratio of the thermal energy and the radiative cooling rate, is generally lower than 1 hr (Priest 1987), radiative losses are negligible in damping the MHD slow modes, which have larger decay times.

Another mechanism that could substantially damp MHD slow-mode waves is phase mixing. Magneto-acoustic waves in a homogeneous medium, in density and temperature, propagate undamped and undisturbed because they are in perfect resonance with each other. However, coronal loops have large density and temperature gradients, especially near the footpoints where the standing waves are reflected. For instance, for MHD slow-mode waves, a density decrease along the coronal loop would increase the sound speed and decrease the wave periods along the magnetic flux tubes. Therefore, standing slow magneto-acoustic waves in a coronal loop might suffer intense phase mixing, during which modes of the same frequency travel with different speed and then have different wavenumbers. As they propagate, they quickly become mutually out of phase, leading to destructive interference, and thus to wave dissipation (e.g., Hood et al. 1997). In other words, the slow MHD modes, which are initially distinct and of a single dominant periodicity, might rapidly decay into a turbulent mixed flow via nonlinear interactions with other reflected modes.

In conclusion, both thermal conduction and phase mixing are viable mechanisms to explain the damping of the observed standing waves which manifest themselves in closed magnetic structures.

5.2. Ray-like Structure Fluctuations

In analogy with the proposed interpretation of the electron density fluctuations in coronal arches, we have evaluated the possibility that outward propagating slow MHD waves might also be responsible for the non-stationary plasma fluctuations detected in a polar region along the magnetic plume-like feature shown in the left panel of Figure 6, which might have an open magnetic configuration.

The density modulation due to propagating MHD waves would result in time shifts of the temporal profiles of the wavelet power inferred along the polar ray. This is because nodes propagate with the wave. Hence, the density fluctuations are expected to be out of phase at different heliocentric altitudes along the open structure, which might act as a channel for outward propagating waves. However, different parts of a ray-like structure are observed to fluctuate in phase, reaching their maximum power quite simultaneously (middle and bottom right panels of Figure 6). No evidence for magneto-acoustic wave propagation in the polar ray-like feature has been found by studying the temporal cross-correlations (method described by Duvall et al. 1993) of the total brightness fluctuations observed at different locations along the structure. This clearly indicates that the plasma density fluctuations detected along the ray of Figure 6 have to be ascribed either to quasi-periodic motion back and forth across the POS of the entire structure or to intrinsic brightness variation of the polar ray itself, likely due to the intermittent nature of the process underlying its generation. As a matter of fact, although the magnetic configuration of solar polar regions is relatively stable, the mechanism driving the formation of the actual ray structure might operate only intermittently (e.g., Wang 1998).

Based on the characteristic timescales of the fluctuations detected in the present analysis, the main mechanism responsible for the temporal variations observed in the brightness of the polar features might be caused by magnetic reconnection, which should be acting with comparable timescales. It has been suggested that magnetic reconnection of continuously emerging flux, guided by supergranular convection, could significantly affect the life cycle of polar plumes, driving multiple hourly occurrences of the plume brightening (e.g., Wang 1998; Raouafi et al. 2008). Magnetic reconnection in polar regions has also been suggested as a source of waves and energy, explaining the fast wind (e.g., Axford et al. 1999). The polar rays observed in coronal maps of the wavelet power are not necessarily observed in coronal brightness maps; thus, they might not always coincide with polar plumes and they are more extended than plumes. The same process of magnetic reconnection can, in principle, act at the base of plumes as well as rays when they do not coincide. Hence, the lifetime of the density fluctuations derived in the present study (of the order of 10 hr; middle right panel of Figure 6) can provide information on both the duration of the intermittent phenomena and on the life cycle of the plume itself, provided the same process is acting at the base of both kinds of structures. Moreover, the characteristic lifetime of the detected fluctuations could also be related to the timescale corresponding to the pronounced tendency of the recurrence of plumes at the same locations (Lamy et al. 1997; DeForest et al. 2001).

6. CONCLUSIONS

This paper reports on the detection of transient periodic or quasi-periodic phenomena occurring in closed and open magnetic structures of the quiet solar corona out to 2 $R_\odot$. The technique used to reveal and characterize the fluctuations is based on the wavelet transforms, which represent a powerful tool to investigate the fine spatial pattern and temporal variability of fluctuating coronal features. Here, this technique has been used to map the variance of the total brightness of the outer solar corona from 1.4 to 4.0 $R_\odot$ for the first time in a systematic way.

The results show that the solar corona is permeated by quasi-periodic recurrent brightness fluctuations, characterized by a wide range of spatial and temporal scales. They are not, however, uniformly distributed but clearly outline the coronal magnetic field, thus appearing to be embedded in fluctuating magnetic structures. Moreover, they are significantly enhanced in regions of stronger field lines. In particular, it has been possible to identify an extended coronal arch in the mid-latitude equatorial region, likely part of a complex equatorial streamer present at the West limb, and a ray structure at high latitudes, both characterized by fluctuations of large amplitude. The arch-like structure is not observed in total brightness maps, thus implying that it is less dense than adjacent coronal structures. In the closed low- and mid-latitude magnetic arch, the observed plasma fluctuations are consistent with the presence of slow magneto-acoustic waves trapped as standing modes and damped on about 10 hr. These waves are very likely stochastically excited by the convective motions at supergranular scales. The most likely mechanisms that could explain the wave damping are thermal conduction and phase mixing. In the polar region, the density plasma fluctuations of the ray structure, not necessarily coincident with a plume and even more extended than a plume, might be interpreted as signatures of intermittent, quasi-periodic magnetic reconnection due to continuously emerging flux tubes. This mechanism, considered to be the most probable for the generation of plumes, as suggested in the literature, can in fact
induce waves and ejections of mass; however, in order to explain the observed fluctuating feature, it should occur in a quasi-periodic recurrent way.

In conclusion, the present study of coronal density fluctuations, which extends previous analyses on periodic or quasi-periodic phenomena to cover the entire solar corona from the limb out to $4 R_\odot$, provides new additional information on the MHD coronal wave properties. The outer solar corona is a region where wave observations have until now been highly fragmentary in space and time. Measurements of the power of MHD waves in the outer solar corona performed in this paper provide an accurate spatiotemporal reconstruction of quasi-periodic plasma phenomena. This may lead to significant progress in determining how the energy carried by MHD waves is transferred from the photosphere to the corona, and dissipated there to accelerate the solar wind.

This work was supported by the Italian Space Agency (ASI) grants (1/023/09/0 and 1/013/12/0). The authors are grateful to the anonymous referee for helpful suggestions leading to a sounder version of the manuscript.

APPENDIX

WAVELET TRANSFORMS AND WAVELET POWER SPECTRUM IN THE ANALYSIS OF THE SOLAR DATA

A.I. General Formalism

Given a wavelet function, $\Psi_0(\eta)$, depending on a non-dimensional “time” parameter $\eta$ that has zero mean and is localized in both time and frequency space, the continuous wavelet transform of an $N$-point discrete two-dimensional time series $f(r, \phi, t)$, sampled at equal time spacing $\delta t$, where $r$ and $\phi$ are, for instance, the spatial polar coordinates and $t = 0, ..., (N-1)\delta t$ is the time, is the convolution of $f$ with a scaled and translated version of $\Psi_0(\eta)$ (Torrence & Compo 1998):

$$W(r, \phi, t, s) = \frac{1}{\sqrt{N}} \sum_{t'=0}^{N-1} f(r, \phi, t') \left( \frac{\delta t}{s} \right) \Psi_0^*(\frac{t' - t}{s}),$$

(A1)

where the asterisk indicates the complex conjugate and $\Psi_0(\eta)$ is normalized to unit energy. By varying the wavelet scale parameter $s$ and translating the wavelet function $\Psi_0(\eta)$ in the time domain, it is possible to determine the amplitude of any periodic feature contained in the data and how this amplitude varies with scale and time. It is worth noting that the wavelet scale $s$ does not necessarily correspond to the Fourier period, $\tau$, because of the functional form of the wavelet function.

The relationship between the equivalent Fourier period and the wavelet scale is derived analytically for a particular wavelet function by substituting a cosine wave of a known frequency $\nu = \pi t^{-1}$ into Equation (A1) and computing the scale $s$ at which the wavelet power spectrum reaches its maximum.

There are a number of different wavelet functions $\Psi_0(\eta)$ with different properties that can be best suited to be applied to different studies. The best choice first depends on its shape and width and whether it is a complex or real valued function. Complex wavelets are ideal candidates for capturing oscillatory behavior with respect to real wavelets, which are more useful for isolating peaks and discontinuities. The width of the wavelet function, namely the $\epsilon$-folding time of the wavelet power, is related to the resolution of the wavelet itself: a narrow function in time has good time resolution but poor frequency resolution and, vice versa, a broad function has poor time resolution and good frequency resolution. Two common mother wavelet functions, both complex, are the Paul and Morlet wavelets. The Paul wavelet is defined as

$$\Psi_0(\eta) = \frac{2^m m!}{\sqrt{\pi}(2m)!} (1 - i\eta)^{-(m+1)},$$

(A2)

where $m = 4$ in the present analysis is the order of the wavelet. The width is $s/\sqrt{2}$ and the wavelet scale $s$ is related to the Fourier period $\tau$ by the expression $\tau = (4\pi/2m + 1)s = 1.4s$.

The Morlet wavelet consists instead of a plane wave modulated by a Gaussian:

$$\Psi_0(\eta) = \pi^{-1/4} e^{i\omega_0 \eta} e^{-\eta^2/2},$$

(A3)

where $\omega_0 = 6$ in the present analysis is the non-dimensional frequency. The width is $\sqrt{2} s$ and the wavelet scale $s$ is related to the Fourier period $\tau$ by the expression $\tau = (4\pi/\omega_0 + \sqrt{2 + \omega_0^2})s = 1.03s$.

The Paul mother wavelet is more sharply defined in time in comparison to the Morlet function. Moreover, it is characterized by few zero crossings, and for this reason it can in principle identify many types of signatures in the power spectrum as sharp variations in the input data and not just oscillatory modes. The Morlet function is narrower in periodicity space than the Paul wavelet, leading to a better frequency resolution. Moreover, it contains more oscillations and then it is optimized for detecting oscillatory signals. Pictures of the real (solid lines) and imaginary (dashed lines) parts of the Paul and Morlet wavelets in both the time domain (top panels) and the frequency domain (bottom panels) are shown in Figure 7.

The wavelet power spectrum is defined as the square of the modulus of the wavelet transform $|W(r, \phi, t, s)|^2$. A vertical slice through the wavelet power spectrum is a measure of the spectrum at a given instant, so that the average of the wavelet power spectrum over the whole observational period, $0 < t < (N-1)\delta t$, gives the global wavelet spectrum, defined as

$$|\bar{W}(r, \phi, t, s)|^2 = \frac{1}{N} \sum_{t=0}^{(N-1)\delta t} |W(r, \phi, t, s)|^2.$$  

(A4)

It is worth noting that the global wavelet spectrum approaches the results that are obtained with the Fourier spectrum of the considered time series (Percival 1995).

The average wavelet power, which is the sum of the power over all of the considered periodicities between $s_1$ and $s_2$, is given by

$$|\bar{W}(r, \phi, t)|^2 = \frac{\delta j \delta t}{C_s} \sum_{j=j_1}^{j_2} |W(r, \phi, t, s_j)|^2,$$

(A5)

where $\delta j (= 0.125$ in the present analysis$)$ is the spacing between the discrete scales commonly defined as fractional powers of two, $s_j = s_0 2^{j}$ ($s_0$ is the Nyquist–Shannon scale), and $C_s$ is the reconstruction factor for the assumed wavelet function (we adopted 1.132 and 0.776 for the Paul and Morlet wavelets, respectively).

The scale-averaged wavelet power defined by Equation (A5) gives a measure of the average variance of the time series as a function of time over the range of periodicities considered in the analysis.
A.2. Cone of Influence

Because of the finite length of the time series, errors will arise at the beginning and end of the wavelet power spectrum, as the Fourier transform assumes the data are cyclic. The COI is defined as the region of the wavelet spectrum where edge effects become important, and is commonly defined as the $e$-folding time for the autocorrelation of the wavelet power at each scale. This $e$-folding time is chosen so that the wavelet power for discontinuity at the edge drops by a factor $e^{-2}$ and ensures that the edge effects are negligible beyond this point.

A.3. Significance Levels

To determine significance levels for a wavelet spectrum, we need to choose an appropriate background spectrum in order to establish a null hypothesis against which the inferred spectrum must be tested. If a peak in the wavelet power spectrum is significantly above the background spectrum, then it can be assumed to be a true feature with a certain percent confidence. In many astrophysical applications, it is a good choice to adopt as a background spectrum a flat spectrum resulting from wavelet analysis of pure white-noise, normally distributed time series. The wavelet coefficients of a normally distributed random variable are normally distributed too; the square of a normally distributed variable is $\chi^2$ distributed with one degree of freedom, $\chi^2$. Hence, in the hypothesis of white-noise normally distributed time series, the wavelet power spectrum would be $\chi^2$ distributed with two degrees of freedom. The 99% confidence contour lines are then determined by multiplying the background spectrum by the 99th percentile value of $\chi^2$; that is $\chi^2(99\%)$.

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