HIGH-FREQUENCY WAVES DETECTED IN THE SOLAR ATMOSPHERE

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ABSTRACT

A spectrum of weakly guided waves in the solar atmosphere at frequencies as high as 100 mHz (10 s period) has been detected with high-cadence solar image sequences from the *Transition Region and Coronal Explorer* (*TRACE*) spacecraft. The waves are visible in the *TRACE* 1600 Å far-UV passband and were detected as faint ridges in an energy spectrum produced by Fourier transformation of subfields of *TRACE* image sequences. They have phase speeds as high as 1 Mm s⁻¹ and group speeds of ~100 km s⁻¹. From the 1600 Å data alone, it is not possible to determine whether the waves are in the chromosphere or transition region. The waves are not energetically significant to the chromosphere but may be significant in the transition region. Two possible excitation mechanisms, small-scale magnetic reconnection or chromospheric shock formation, are identified and will guide future work. The waves may prove to be a useful probe into local conditions and energy release into the solar atmosphere.

Subject headings: Sun: chromosphere — Sun: oscillations — Sun: transition region

1. INTRODUCTION

Wave energy transport is important for chromospheric and coronal heating (e.g., Carlsson et al. 1997; Carlsson & Stein 2002; Davila 1987; Hollweg 1984; Walsh & Ireland 2003) and solar wind acceleration (e.g., Cranmer 2002; Habbal et al. 1996). For a recent review, see Aschwanden (2003). The wave field above 10 mHz may transport a large but as yet undetected amount of energy through the chromosphere, transition region, and corona and into the solar wind; and the frequency spectrum and spatial distribution of such waves would form powerful probes of small-scale physics in the solar atmosphere.

The strength and frequency distribution of the high-frequency wave field are important to measure and difficult to predict, because the photospheric motion does not contain much energy above 20 mHz (e.g., Kosovichev et al. 1997 and references therein): such waves must be created locally by turbulent cascades or by rapid but as yet poorly understood events such as small-scale magnetic reconnection. Hence, high-frequency waves should be useful to probe not only local conditions in the medium through which they propagate but also the mechanisms of energy release in the solar atmosphere.

Several studies have searched for evidence of high-frequency oscillations in the lower solar atmosphere, representing trapped waves in small loops. Eclipse observations in the coronal green line (e.g., Rudawy et al. 2004; Williams et al. 2002; Pasachoff et al. 2002) have shown oscillations in the 1–10 Hz band. But direct evidence of high-frequency propagating waves has been elusive.

The highest order photospheric *P*-modes are readily characterized because they exist in a two-dimensional waveguide formed by the negative vertical sound speed gradient in the upper convection zone; waves that are launched downward are refracted upward to interfere with similar waves that happen to be traveling closer to the surface. A similar waveguide exists in the upper solar atmosphere, above the temperature minimum; both the Alfvén and sound speeds increase with altitude above the temperature minimum into the base of the corona, leading to the possibility that fast-mode waves, which are otherwise only weakly guided by the magnetic field, could be guided and form a similar ridge spectrum by a similar refractive mechanism. Hence, a good way to try to detect the high-frequency wave field is by Fourier analysis of rapid UV image sequences, to identify whether a ridge spectrum is present. In this Letter, I present such a study using 2.7 s cadence far-UV images obtained by the *Transition Region and Coronal Explorer* (*TRACE*; Handy 1999) in 2003 January.

2. OBSERVATIONS

Near the end of 2002 and beginning of 2003, *TRACE* collected several data sets in its 1600 Å channel. This passband admits a mixture of UV continuum from the chromosphere and the C IV 1550 Å doublet from the transition region. These runs were uncompressed to save processor time and consequently had no degradation by lossy compression. The runs lasted for 20–40 minutes each, limited by the amount of onboard memory. The present analysis is based on two observing runs from the morning of 2003 January 3 with the same pointing, lasting for a total of just over 1 hr. Two quiet-Sun subfields were used. Figure 1 shows a typical *TRACE* frame (after preprocessing) from this period and the two subfields that were analyzed.

3. DATA REDUCTION

Because weak-signal detection is subject to many forms of systematic error, great care is required to condition the *TRACE* data and produce a wave spectrum. Individual detected wave components have an amplitude as little as 0.1 detector count, averaged over an entire image sequence; improperly despiked or aligned images can produce noise components that easily swamp such a faint signal. Here I describe each of the steps required to reproduce the result. The pipeline was implemented in the Perl Data Language (Glazebrook et al. 2003).

3.1. Cosmic-Ray Removal

Virtually all space-based solar image sequences contain spikes due to cosmic rays and other particles. *TRACE* 1600 Å images have high contrast in small features; this confuses traditional spatial despiking algorithms because many spikes are no larger than the desired solar features. I used the *zspike* despiking algorithm, which treats each spatial pixel completely independently. Each frame f_i in the sequence is compared to the set of neighbor frames $[f_{i-n} \dots f_{i+n}]$. Each of the neighbor frames f_j is compared pixelwise with f_i to produce a pair of mask frames p_{ii} and n_{ii} that indicate whether the central frame is more than a



FIG. 1.—A destretching operation compensates for perspective foreshortening and spacecraft jitter. *Left*: Original image with solar longitude/latitude grid superposed. *Right*: Destretched image. The lines of latitude are almost imperceptibly curved because they are not great circles. The two "quiet-Sun" fields of view are shown.

set threshold above or below the neighbor value. These positive and negative "vote masks" are combined with a voting algorithm to produce a spike mask m_i that is nonzero only where a majority of neighbors "vote" that the central frame has too high a value *and* no neighbors vote that the central frame has too low a value. For these data, I used n = 2 and a threshold value of 30 *TRACE* digitizer counts ("DN"; or 35 DN s⁻¹). Three (of four possible) votes were required to label a spike. Spikes were replaced with the mean of the pixel value from the previous and next images.

3.2. Read Noise Removal

TRACE data contain wavelike artifacts due to radio frequency interference (RFI) between the spacecraft electronics and the analog side of the camera readout (T. D. Tarbell 2003, private communication). These artifacts could in principle emulate traveling waves in the solar atmosphere, so some effort went into removing them.

The periodic nature of the noise produces a wavy pattern in each image and spikes in the Fourier plane of each image. Because the interference and the camera are not locked together,



Magnitude FFT of TRACE difference image

FIG. 2.—Spatial power spectrum of the difference of two images taken 2.7 s apart, showing solar variation (*faint ring at about* 0.6 $\operatorname{arcsec}^{-1}$) and camera RFI read noise (*circled spikes*).

the relative frequencies drift with time. The oscillations have a typical amplitude of a few DN peak to peak, with isolated frames demonstrating 5–30 DN peak-to-peak amplitudes.

Figure 2 contains the explanation for the variable amplitude of the read noise; when the high-frequency fundamental and its harmonics happen to line up in a straight line, then a single, coherent pattern with high amplitude appears in the image. When the components do not happen to line up in a straight line, then the corresponding pattern is more complex and less visible to the observer's eye, and the typical peak-to-peak amplitude is less (although in a few isolated places, it is greater).

I used a simple despiking algorithm to replace the spiky components with their enantiomorphic components reflected through the *Y*-axis. The noise was reduced by more than an order of magnitude. In case any of the myriad weak nearly horizontal components remained, I ignored wave *k*-vectors within 10° of the *X*-axis in the subsequent analysis.

3.3. Image Destretching and Stabilization by Cross-Correlation

Image destretching was required to remove the effects of foreshortening on apparent wave speed and is illustrated in Figure 1. If waves are propagating at a uniform speed in all directions, then the projected speed in the image plane will appear reduced in the direction of foreshortening in unprocessed images; perspective destretching equalizes the apparent wave speed. The despiked, denoised images were destretched using an orthographic spherical perspective, to appear as if they were acquired at disk center. To eliminate pointing drift and the small amount of solar rotation, individual images were resampled with small subpixel displacements that were fitted to maximize cross-correlation between adjacent frames in a 50×50 pixel region near the center of the field of view.

To minimize artifacts, I performed the displacement and destretching in a single resampling step. For a given image pair, I resampled the image under a compound coordinate transform $T = P \circ D$, where P is the orthographic perspective rotation and D is a displacement ("pointing error") in the original image plane. The resampling used a spatially variable antialiasing filter to avoid artifacts (DeForest 2004). A simple amoeba alQuiet Sun θ -averaged 1600 Å wave diagram



FIG. 3.—*TRACE* k- ω diagram showing faint ridges near 100 mHz; several are marked. This is a negative print: darker features are stronger. The range spans one half-decade on a logarithmic scale. Two fiducial wave speeds are marked on the diagram. Slow solar evolution saturates the lower portion of the image. Features along the k = 0 axis may be due to variations in exposure time.

gorithm (Press et al. 1986) found the displacement that maximized the correlation coefficient between adjacent resampled frames.

3.4. Apodization

To prevent "ringing" of high-frequency components at the boundaries of the data, I apodized the data. Each axis (x, y, t) of the destretched and aligned data cube was multiplied by a strict Hanning windowing function $h(x) = [\sin (\xi x)]^2$, where ξ is a constant such that ξx ranges from 0 to π . The Hanning apodization is rather severe, discarding half of the "weight" of the data on each axis, but it has the advantage that its spectrum completely lacks subsidiary peaks beyond the minimum resolvable frequency and therefore there is no possibility of "imaging" strong components into a spectrum of subsidiary peaks in the final Fourier plane.

3.5. Fourier Transformation and Summing

Three-dimensional Fourier transformation converts the selected region to the k_x , k_y , ω basis. In this basis, plane waves propagating at a particular speed all lie on a cone with cone angle arctan v, where v is the wave speed.

If local variations in the magnetic field are neglected, there is only one strongly preferred direction—the vertical one—in the lower solar atmosphere. Following the *Ansatz* that wave propagation is nearly isotropic in the horizontal plane, I increased the signal-to-noise ratio by transforming into cylindrical (θ , k_r , ω) coordinates and summing over θ . To eliminate potential remnant RFI noise components along the k_x -axis, I eliminated all directions within 10° of horizontal, resulting in a total of 280° being included in the final sum. After coherent summing in θ , I extracted the magnitude of the complex Fourier component values, to yield a magnitude k- ω diagram of wavelike motions found in the original image sequence.

I generated a k- ω diagram for each of 12 200-frame (9 minute) sequences, selected for no missing frames and no excessive energetic-particle rates. These diagrams were averaged together



FIG. 4.—Null test demonstrating spoilage of the wave signal by shuffling. The brightness scale is a full decade to prevent saturation in the horizontal noise bands. The ridges from Fig. 3 are not present.

incoherently to produce an averaged k- ω diagram for the quiet Sun across the different intervals and two subfields, with a total of 108 minutes of integration. The apodization reduced the effective pixel weight by a factor of 8, yielding a noise signature equivalent to only 14 minutes of integration.

3.6. Null Testing

I performed a simple null test, using the exact same analysis pipeline as the main analysis but with the images in a shuffled temporal order. The shuffling randomized the order of each group of 5-20 frames (10–55 s), progressing sequentially through the data with a group size that was selected randomly at each step. This local shuffling limits the amount of noise injected by discontinuities in the slow solar evolution across the shuffled images, while spoiling the time signature of rapid motions.

This form of null testing eliminates the two most plausible sources of an injected, artificial wave signal: RFI that is not cleaned up by the denoising step or residual jitter in the images. Both of these mechanisms result in incoherent motions that might produce ridges in the amplitude Fourier spectrum; but, being incoherent, they should be unaffected by shuffling of the data. The real wave signal is spoiled by the shuffling; if the ridges represent real spectral features, one expects to *not* see them in the shuffled k- ω diagram.

4. RESULTS

Figure 3 is the time-averaged quiet-Sun k- ω diagram. Diagonal, ridge features are visible, slightly above the noise threshold; four of them are marked in the frequency range 50– 100 mHz. The more well-known photospheric and chromospheric oscillations are at ~3 and ~5 mHz, respectively; both are subsumed within the low-frequency solar evolution signal. The range of the figure is a factor of 3 in intensity; the waves are a factor of ~1.5 above the noise floor. The spatial and temporal Nyquist frequencies are 1.0 Mm⁻¹ and 180 mHz, respectively. The phase speeds of the ridges are several hundred kilometers per second; and the group speeds (determined by the slope) are close to 100 km s⁻¹.

Figure 4 shows the results of the null test. The frame shuffling

Vol. 617

had the effect of mixing some of the solar evolution signal into higher temporal frequencies, resulting in randomly placed, large horizontal bands in the k- ω diagram. To prevent saturation by the bands, I expanded the dynamic range by a factor of 2, to a full decade in intensity. The ridges that are visible in Figure 3 would, if present, be apparent here at about one-third the amplitude of the strongest horizontal bands; but they are not present.

5. DISCUSSION AND CONCLUSIONS

Figure 3 is direct evidence that guided waves exist in the parts of the solar atmosphere that are imaged by the *TRACE* 1600 Å band. The dark ridges in the figure are particular wave modes that are distinguished by different phase speeds. The cross-ridge profile is consistent with a single- or multiple-bounce interference. The evidence of vertically guided waves is strong because few mechanisms other than a waveguide can produce the observed, recognizable ridge structure.

The waves are most likely a compressive MHD mode, because the *TRACE* images are only sensitive to changes in intensity. A plausible explanation is that the intensity fluctuations are fast-mode waves that propagate at an angle to the magnetic field and are refracted downward by the vertical gradient of the Alfvén speed between the chromosphere and corona. The situation may be more complex; simulations of waves emanating from small magnetized regions in the solar atmosphere show complex moving interference patterns that form around the $\beta = 1$ surface and propagate at speeds that are different than either the fast or slow speed (Bogdan et al. 2003).

Typical ridge pixels are typically a factor of 1.5 enhanced over the noise background, amounting to a signal level of 0.1–0.3 DN pixel⁻¹ (one mode and frequency) or a total wave amplitude of less than 10 DN pixel⁻¹ (all detected modes and frequencies). This is a total relative amplitude of 2%–3%. But the *TRACE* 1600 Å band includes two widely separated spectral components. The waves might be ~3% disturbances visible in the dominant UV continuum or ~30% disturbances in the fainter C IV 1550 Å contribution. If the moving features are direct wave trains, rather than more complex interference patterns, then these cases correspond to an order of 1 kW m^{-2} of horizontal mechanical energy flux in either the chromosphere or the transition region, respectively; coincidentally, the stronger required relative amplitude in the transition region case approximately cancels the lower pressures found there.

Future work will compare wave spectra obtained in different *TRACE* far-UV spectral bands to determine the altitude at which the waves exist; if the waves are present primarily in the transition region, then the signal should be absent in *TRACE* 1700 Å band image sequences. Contrariwise, if the waves are primarily in the chromosphere, the signal should be stronger in *TRACE* 1700 Å band image sequences than in the (current) 1600 Å data sets.

The present analysis does not provide any information on the temporal characteristics of the waves: whether they are resonant, continuous notes; single excitations of local resonators; "chirps" produced by evolving systems or dispersion; or single pulses produced by impulsive processes such as reconnection or spicule motion. The photospheric granulation field has little or no energy above 20 mHz, so these waves must be excited by a different mechanism than direct buffeting. Plausible source mechanisms include chromospheric shocks, from 3 minute oscillations, spicular pistons, or the upward leakage of 5 minute oscillations (De Pontieu et al. 2003); and smallscale, rapid magnetic reconnection. If magnetic reconnection is the source, then the waves should have higher amplitude in magnetized regions such as plage than in the quiet Sun.

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