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The Hunt for the Missing Modes: Revealing the True Nature of the Solar Wind

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14. ABSTRACT
This effort produced a novel image-processing algorithm which has allowed successful identification and accurate track of solar plumes in Solar Dynamics Observatory/Atmospheric Imaging Assembly (SDO/AIA) data and, moreover, enabled the first direct measurements of transverse waves in solar polar plumes. This image-processing technique has allowed direct measurement of the transverse displacements, periods and velocity-amplitudes of 596 distinct oscillations in the 171Å channel (over a 4 hour period) which displayed a non-uniformly distributed range of parameters. Furthermore, the measurements allow us to take into account the whole of observed non-uniform parameter distribution, permitting the calculation of a more accurate time-averaged energy flux than previously reported. Crucially, this allowed the calculation of an energy flux of 9-24 W m⁻², which is 4-10 times below the energy requirement for solar wind acceleration. Hence, the results indicate that transverse magnetohydrodynamic waves as resolved by SDO/AIA cannot be the dominant energy source for fast solar wind acceleration in the open-field corona.
The development of this robust, versatile wave-tracking image-processing algorithm can also be applied to a whole range of different solar structures (and in principle to other data sets that display oscillation behaviour). For example, we took advantage of the recent High-resolution Coronal Imager (Hi-C) data and applied the image-processing algorithm to measure the fine-scale structure in transition region moss which led to the first direct observation of transverse wave behaviour of moss in an active region.

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Summary

The accomplishments of the effort were:

- The two key scientific questions were addressed (details below)
- Two peer-reviewed journal papers were written and published:
 - Thurgood, Morton & McLaughlin, 2014, *Astrophysical Journal Letters*, **790**, L2;
 - Morton & McLaughlin, 2014, *Astrophysical Journal*, **789**, 105
- The results were disseminated via:
 - an international invited talk in Republic of Korea, and
 - at the National Astronomy Meeting 2014, with the presentation then going on to win the *Royal Astronomical Society's* Best Postdoc Poster prize.

Introduction

Grant FA8655-13-1-3067 addressed two key scientific questions:

- Determine the fundamental properties of solar plumes and understand their link to the solar wind.
- Detect fast magnetoacoustic and Alfvén waves in plumes (as theoretically predicted).

Methods, Assumptions, and Procedures

It was clear that for the first part of this project we needed to develop and apply an image-processing algorithm to accurately (i) identify individual plumes, (ii) track their evolution through time. Such identification and tracking was achieved using an automated Gaussian-fitting method. This newly-developed algorithm identifies local intensity peaks in the region of interest, and the accuracy of the position is then refined to sub-pixel accuracy by fitting the neighbourhood (centred around the point) with a Gaussian. These local intensity maxima are then tracked through the time series by utilising a crawling technique to check the neighbouring pixels to identify precisely the local maximum. These automatically-detected threads are the time-series of the solar plumes we are interested in. We fit the data with a sinusoidal and linear trend, using a Levenberg-Marquardt least-squares minimization.

Results and Discussion

This novel image-processing algorithm has allowed us to successfully identify and accurately track solar plumes in Solar Dynamics Observatory/Atmospheric Imaging Assembly (SDO/AIA) data and, moreover, has allowed us to report the **first direct measurements of transverse waves in solar polar plumes** [see Paper 1 below] – i.e. achieving one of our key scientific questions. Our image-processing technique has allowed us to directly measure the transverse displacements, periods and velocity-amplitudes of 596 distinct oscillations in the 171Å channel (over a 4 hour period) which displayed a non-uniformly distributed range of parameters. Furthermore, our measurements allow us to take into account the whole of our observed non-uniform parameter distribution, permitting us to **calculate a more accurate time-averaged energy flux than previously reported**. Crucially, this allowed us to calculate an energy flux of 9-24 W m⁻², which is 4-10 times below the energy requirement for solar wind acceleration. Hence, our results indicate that **transverse magnetohydrodynamic waves as resolved by SDO/AIA cannot be the dominant energy source for fast solar wind acceleration in the open-field corona**.

We have developed a robust, versatile wave-tracking image-processing algorithm which can also be applied to a whole range of different solar structures (and in principle to other data sets that display oscillation behaviour). For example, we took advantage of the recent *High-resolution Coronal Imager* (Hi-C) data and applied our image-processing algorithm to measure the fine-scale structure in transition region mass leading to the **first direct observation of transverse wave behaviour of moss in an active region** [see Paper 2 below].

As a direct result of the effort, two high-impact peer-reviewed journal papers have been published so far:

- **Paper 1**

Thurgood, J.O., Morton, R.J. & McLaughlin, J.A. (2014)

[First direct measurements of transverse waves in solar polar plumes using SDO/AIA](#)

Astrophysical Journal Letters, **790**, L2

DOI = 10.1088/2041-8205/790/1/L2

[abstract]

There is intense interest in determining the precise contribution of Alfvénic waves propagating along solar structures to the problems of coronal heating and solar wind acceleration. Since the launch of SDO/AIA, it has been possible to resolve transverse oscillations in off-limb solar polar plumes and recently McIntosh et al. concluded that such waves are energetic enough to play a role in heating the corona and accelerating the fast solar wind. However, this result is based on comparisons to Monte Carlo simulations and confirmation via direct measurements is still outstanding. Thus, this Letter reports on the first direct measurements of transverse wave motions in solar polar plumes. Over a four hour period, we measure the transverse displacements, periods, and velocity amplitudes of 596 distinct oscillations observed in the 171 Å channel of SDO/AIA. We find a broad range of non-uniformly distributed parameter values which are well described by log-normal distributions with peaks at 234 km, 121 s, and 8 km s⁻¹, and mean and standard deviations of 407 ± 297 km, 173 ± 118 s, and 14 ± 10 km s⁻¹. Within standard deviations, our direct measurements are broadly consistent with previous results. However, accounting for the whole of our observed non-uniform parameter distribution we calculate an energy flux of 9-

24 W m^{-2} , which is 4-10 times below the energy requirement for solar wind acceleration. Hence, our results indicate that transverse magnetohydrodynamic waves as resolved by *SDO/AIA* cannot be the dominant energy source for fast solar wind acceleration in the open-field corona.

- **Paper 2**

Morton, R.J. & McLaughlin, J.A. (2014)

[High-resolution Observations of Active Region Moss and its Dynamics](#)

Astrophysical Journal, **789**, 105

DOI = 10.1088/0004-637X/789/2/105

[abstract]

The *High Resolution Coronal Imager* has provided the sharpest view of the EUV corona to date. In this paper, we exploit its impressive resolving power to provide the first analysis of the fine-scale structure of moss in an active region. The data reveal that the moss is made up of a collection of fine threads that have widths with a mean and standard deviation of $440 \pm 190 \text{ km}$ (FWHM). The brightest moss emission is located at the visible head of the fine-scale structure and the fine structure appears to extend into the lower solar atmosphere. The emission decreases along the features, implying that the lower sections are most likely dominated by cooler transition region plasma. These threads appear to be the cool, lower legs of the hot loops. In addition, the increased resolution allows for the first direct observation of physical displacements of the moss fine structure in a direction transverse to its central axis. Some of these transverse displacements demonstrate periodic behavior, which we interpret as a signature of kink (Alfvénic) waves. Measurements of the properties of the transverse motions are made and the wave motions have means and standard deviations of $55 \pm 37 \text{ km}$ for the transverse displacement amplitude, $77 \pm 33 \text{ s}$ for the period, and $4.7 \pm 2.5 \text{ km s}^{-1}$ for the velocity amplitude. The presence of waves in the transition region of hot loops could have important implications for the heating of active regions.

In addition to generating a lot of interest scientifically (at conferences, via email discussions, etc), the project and papers have also generated several other indicators of esteem / significance already:

- **[invited speaker]** Dr James McLaughlin was an invited speaker and presented the results of Paper 1 at the *AGU Chapman Conference on Low-Frequency Waves in Space Plasmas* (Jeju Island, Republic of Korea) in September 2014.
- **[awards/prizes]** Dr Jonathan Thurgood won the Royal Astronomical Society's Best Postdoc Poster prize for his presentation of the results of Paper 1 at the National Astronomy Meeting 2014 (Portsmouth, UK).
- **[press release]** The results of Paper 2 were accompanied by a press release hosted by the Royal Astronomical Society ([Solar moss shakes at 16,000 km an hour](#)) which was then picked-up by, e.g., [Phys.org](#) .

Feedback

The grant also received feedback from AFRL scientists (received late September 2014):

"At the very least, these results are pretty interesting and possibly rather important. As you know, exactly how the solar wind is accelerated is still an open debate. As I understand it, a lot of models are beginning to use Alfvén waving heating as a method to accelerate the solar wind. These results seem to suggest this may not be the right approach/mechanism. It's not clear to me that their work will resolve the issue, but it might provide important new clues to the problem."

References

- Morton, R.J. & McLaughlin, J.A. (2014)
[High-resolution Observations of Active Region Moss and its Dynamics](#)
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