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MATTERS ARISING

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Reply to: Signatures of sunspot oscillations and the case for chromospheric resonances

David B. Jess[1,2]✉, Ben Snow[3], Bernhard Fleck[4], Marco Stangalini[5,6] and Shahin Jafarzadeh[7,8]

REPLYING TO T. Felipe *Nature Astronomy* https://doi.org/10.1038/s41550-020-1157-5 (2020)

In our paper[1], we studied a fully formed active region that was approximately halfway through its evolutionary lifecycle, and examination of the Fourier-derived spectral energies of the sunspot umbra revealed a spectral 'bump' at ~20 mHz. Furthermore, the spectral gradients following the ~20 mHz energy enhancement changed progressively across the umbral diameter, implying that they may reflect the intrinsic characteristics of the underlying umbral atmosphere. Numerical simulations of the sunspot atmosphere, harnessing the Lagrangian–Eulerian remap[2] (LareXd) code, also revealed spectral energy variability at ~20 mHz (including changing spectral slopes). These results were consistent with the pioneering theoretical work of Botha et al.[3] and Snow et al.[4], allowing us to interpret these as a signature of wave resonance arising from the temperature gradients naturally occurring in the solar photosphere and transition region. At the time of publication, we recognized that we had observed strong evidence of resonance behaviour in a single, isolated sunspot structure. As a result, in the supplementary information of our paper[1], we openly posed a number of key outstanding questions, and requested that the community examine sunspot wave phenomena on a statistical basis to verify how commonplace resonance signatures are.

The Matters Arising by Felipe[5] highlights the observational and modelling challenges facing solar physicists in the modern era of high temporal, spatial and spectral resolutions. We welcome this particular side of his communication, as it directly reflects the open questions we posed in the supplementary information of our Letter. Considering our paper, Felipe remarks that: (1) the observational power spectra of sunspots do not always demonstrate consistent signatures that can be used as an indicator for the presence of a resonance cavity; (2) theoretical time series can generate spectral energy enhancements that are not solely linked to resonance effects; and (3) the interplay between linear and nonlinear effects is likely to play a role in the features observed in both simulated and observed power spectra. In the following, we address the points raised by Felipe to highlight the importance of ongoing research in this challenging scientific field.

He I 10830 Å sunspot observations

Felipe highlighted that the observations we presented were "extraordinary". The quality of the atmospheric seeing can be estimated by the root mean squared (r.m.s.) fluctuations required to co-align (on a sub-pixel level) successive image from our time series. For this task, the contemporaneous 4170 Å blue continuum imaging observations obtained with the Rapid Oscillations in the Solar Atmosphere[6] (ROSA) instrument were employed, as these were acquired with short exposure times (5 ms) to prevent any seeing-induced smearing from effecting the cross-correlations, and the highest cadence (2.11 s after image reconstruction). In total, there were 2,468 ROSA frames, spanning 5,207.48 s (~87 min). Figure 1 documents the absolute sub-pixel shifts in both solar north–south and east–west directions, calculated from the cross-correlation coefficients. At a time of ~2,835 s into the observing sequence, there is a degradation of the image quality caused by a passing cirrus cloud. However, the original adaptive optics (AO) lock point was restored once this had completely passed (at ~3,060 s) and the pointing accuracy continued to be excellent until 5,100 s, when the seeing degraded and we terminated the observations. On the basis of the raw (sub-pixel) shifts, the r.m.s. fluctuations are 0.070″ and 0.073″ for the solar east–west and north–south directions, respectively. These r.m.s. pointing fluctuations are less than half of our He I 10830 Å pixel sampling (0.15″ per pixel), showing the high image stability achieved during our observations.

We believe that the excellent seeing conditions are responsible for the clarity of the heightened spectral energy bump at ~20 mHz. To test this hypothesis, we generated time- and wavelength-dependent point spread functions (PSFs) corresponding to 0.75″, 1.00″ and 1.50″ seeing conditions. The PSFs model the AO residual aberrations at the Dunn Solar Telescope focal plane for the three different seeing conditions. These were obtained from simple closed-loop AO numerical simulations carried out with the PAOLA simulation code[7]. These PSFs, specific to the He I 10830 Å line, were convolved with the original spectra to degrade its spatial resolution, before recomputing the corresponding spectral energy densities. Figure 2 reveals the importance of seeing conditions when exploring the high-frequency regime, with the secondary bump at ~20 mHz reduced with 0.75″ seeing, barely visible with 1.00″ seeing and completely suppressed with 1.50″ seeing conditions. Furthermore, it can be seen from Fig. 2 that the steepness of the spectral slope following the dominant peak at ~6 mHz is dependent on the quality of the local seeing conditions, with higher frequency fluctuations heavily damped (by more than an order of magnitude) as the seeing conditions degrade. Therefore, spectral energy spectra showing very steep gradients immediately after the universal ~6 mHz dominant peak may not be suitable for such resonance studies, which require prolonged periods of excellent seeing conditions. Hence, the importance of spatial resolution, which is often intrinsically coupled

[1]Astrophysics Research Centre, School of Mathematics and Physics, Queen's University Belfast, Belfast, UK. [2]Department of Physics and Astronomy, California State University Northridge, Northridge, CA, USA. [3]Centre for Geophysical and Astrophysical Fluid Dynamics, University of Exeter, Exeter, UK. [4]Science and Operations Department, ESA, Greenbelt, MD, USA. [5]Italian Space Agency (ASI), Rome, Italy. [6]INAF-OAR National Institute for Astrophysics, Monte Porzio Catone (RM), Italy. [7]Institute of Theoretical Astrophysics, University of Oslo, Oslo, Norway. [8]Rosseland Centre for Solar Physics, University of Oslo, Oslo, Norway. ✉e-mail: d.jess@qub.ac.uk

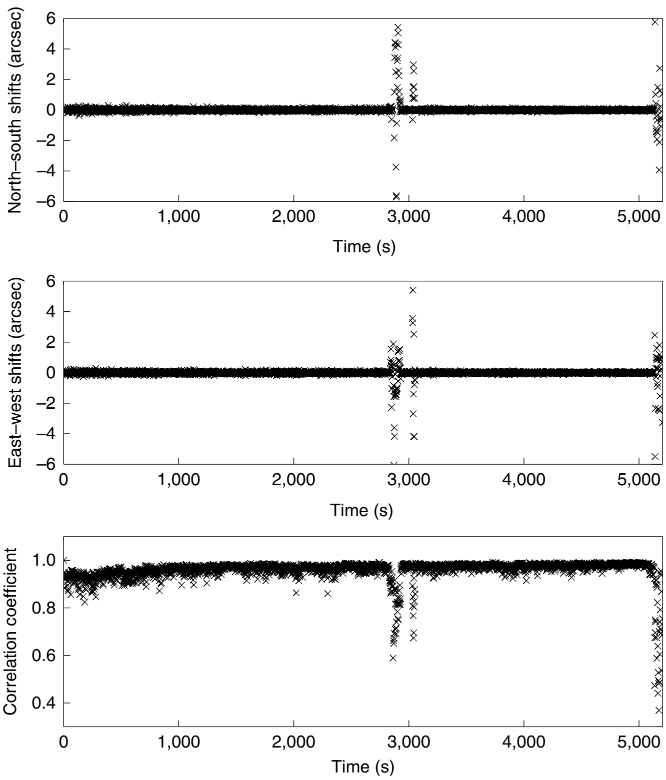

Fig. 1 | The telescope pointing stability achieved on 2016 July 14. The rigid shifts in both the solar north–south (top) and east–west (middle) directions required to co-align consecutive ROSA 4170 Å continuum images, which were acquired contemporaneously with our He I 10830 Å spectra, are shown for the duration of the observations presented in ref. [1]. The image-by-image cross-correlation coefficients (bottom) are high, a result of solar north–south and east–west r.m.s. fluctuations on the order of 0.073″, demonstrating excellent seeing conditions. The increased fluctuations seen at times of ~2,835 s and ~5,100 s are caused by the passing of a thin cirrus cloud, with the latter resulting in the termination of the observing sequence.

with the local seeing conditions at the telescope, cannot be overestimated when attempting to isolate and quantify high-frequency wave signals in spectroscopic time series. This may be a factor in the relatively small enhancements in the spectral energies depicted by Felipe in his fig. 1 (that is, small excesses above his calculated 99% confidence levels) at ~20 mHz.

As a result, we wish to emphasize that we are looking forward to the rise of solar cycle 25, which will hopefully be accompanied by new, even higher quality observations from the National Science Foundation's Daniel K. Inouye Solar Telescope[8] (DKIST), which can probe the small-scale spectral energy fluctuations of sunspots with unprecedented precision. We expect that DKIST will provide higher precision polarimetry, extended periods of excellent seeing conditions and better spatial resolution, which should be able to tell us whether the sunspot documented in Jess et al. is truly exceptional or not.

Numerical modelling and the effects of nonlinearities

Felipe provided evidence that different numerical simulation codes can demonstrate spectral enhancements at ~20 mHz that are linked to nonlinear harmonics of the dominant ~6 mHz peak, rather than pure wave resonance. We must stress that the simulations developed for our work were constrained by our observational findings, with a He I 10830 Å r.m.s. velocity amplitude on the order of ~3.5 km s^{-1}. Hence, the waveforms present in our observations demonstrated predominantly linear traces, with minimal 'sawtooth' structuring that would indicate the presence of developing (nonlinear) shocks, which was shown in fig. 2 of ref. [1]. However, although our observations contained predominantly linear waveforms (r.m.s. ≈ 3.5 km s^{-1}), on occasion we did detect velocity amplitudes rising above ~10 km s^{-1}, approaching the local sound speed in these instances. As a result, the effects of borderline nonlinearities cannot be excluded entirely from a potential interpretation as steep transitions in velocity space are difficult to resolve with the temporal cadence (14.6 s between spectra) of our observations. This again highlights the importance of upcoming DKIST observations, including the use of instruments such as the Diffraction Limited Near Infrared Spectropolarimeter (DL-NIRSP), which will enable simultaneous two-dimensional spatial mapping of the He I 10830 Å line to be obtained with high polarimetric precision and a spatial resolution as high as 0.06″ (some five times higher than the data presented in our study). The increased polarimetric precision will enable more accurate inversions to be achieved, the greater spatial resolution will enable the precise high-frequency energy structuring of sunspots to be deduced with greater clarity and the two-dimensional fibre-fed nature of the instrument will allow the entire sunspot to be studied simultaneously.

It is also worth noting that wave behaviour often demonstrates strikingly different signatures when modelled separately through the assortment of available numerical magnetohydrodynamic (MHD) simulations, including the LareXd, MANCHA[9], BiFrost[10], CO^{5}BOLD[11] and MuRAM[12] codes. Each code provides specialist and refined treatment of physics to tackle different problem sets, whether related to shock-capturing environments or the investigation of partial ionization effects. As such, it may come as no surprise that different MHD codes may produce different output signatures when modelling the complex lower solar atmosphere. Indeed, fig. 2 presented by Felipe[5] shows a very sharp decrease in spectral energy at ~15 mHz, by almost an order of magnitude, which is not consistent with the more smoothly transitioning spectral energies found in both our observations and models, nor the observations presented by Felipe in his fig. 1.

It is imperative that future research attempts to uncover the physics and numerics that accurately replicate the umbral atmosphere. Recent findings[13,14] have put forward new approaches to more accurately model the interaction of the transition region with the surrounding atmosphere, which may help to determine the resonance effects at work in sunspot umbrae. In addition, numerical codes can elect to extract information at either constant temperatures or constant geometric heights. The He I 10830 Å spectral line is formed at ~10,000 K (ref. [15]) or a geometric height of ~2,100 km, so a future examination and comparison of the resulting velocity fluctuations between constant isotherms and atmospheric heights may shed light on the resonant MHD wave interactions with the solar transition region. With this in mind, it is also important to evaluate whether the resonant signatures (spectral enhancement at ~20 mHz and the variability of subsequent spectral slopes that map the thickness of the underlying cavity) are visible throughout the resonance cavity at different temperatures and/or geometric heights. Furthermore, the effects of r.m.s. velocity amplitudes on their corresponding spectral energies need to be documented in a statistical and thorough manner. For example, how do developing shock fronts, oscillation harmonics and even shock-induced resonances and refractions[16,17] affect the ability to extract purely resonant signatures from the associated spectra? As a result, and in agreement with the general findings put forward by Felipe, we believe that more research, development and benchmarking needs to be undertaken in relation to the numerical MHD codes researchers now have at their disposal. Understanding the dominant mechanisms at work in the lower solar atmosphere will allow numerical codes to more accurately replicate the underlying physics synonymous with these tenuous layers of the Sun's atmosphere, and hence

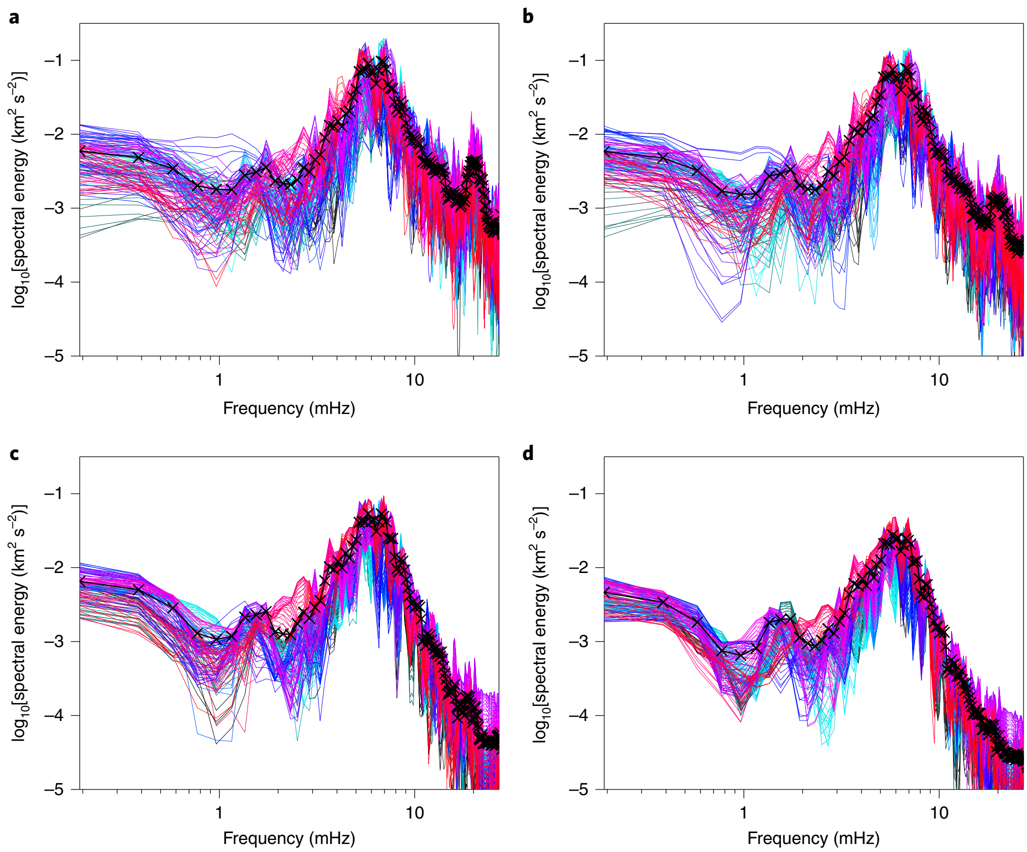

Fig. 2 | Spectral energies of the original and degraded He I 10830 Å observations. a–d, The calculated He I 10830 Å spectral energies of the original data products (**a**), and those degraded by convolving time- and wavelength-dependent PSFs corresponding to 0.75″ (**b**), 1.00″ (**c**) and 1.50″ (**d**) seeing conditions. The coloured lines represent spectra derived across the entire sunspot umbral diameter (shaded blue to pink), whereas the solid black lines represent the average umbral spectral energies. It is clear that reduced image quality, caused by worsening seeing conditions and hence poorer spatial resolution, reduce the clarity of high-frequency fluctuations and promote a more rapid spectral energy decline after the dominant ~6 mHz peak.

better reflect the characteristics manifesting in current and upcoming observational datasets.

Final remarks

Felipe's Matters Arising, based on the open questions posed in our paper[1], provides important additional observational and modelling results that can help to shape research linked to waves manifesting in sunspot umbrae. Although fig. 1a of Felipe's work may reveal slight spectral energy enhancements at ~20 mHz that are above his calculated 99% confidence levels, they are not as prominent as those found in our observations. On the basis of Figs. 1 and 2, we hypothesize that this may be linked to our extraordinary dataset, captured through harmonious use of modern instrumentation, excellent seeing conditions, high-order AO, high-precision polarimetry calibrations and an efficient ground-based telescope facility. Upcoming DKIST observations are therefore of paramount importance for verifying or refuting the absolute role of wave resonances in sunspot umbrae. We wholeheartedly agree with Felipe that there is a need for more in-depth examinations of wave activity in modern observations and simulations, which, again, is consistent with the open questions we posed[1].

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References

1. Jess, D. B. et al. A chromospheric resonance cavity in a sunspot mapped with seismology. *Nat. Astron.* **4**, 220–227 (2019).
2. Arber, T. D., Longbottom, A. W., Gerrard, C. L. & Milne, A. M. A staggered grid, Lagrangian-Eulerian remap code for 3-D MHD Simulations. *J. Comput. Phys.* **171**, 151–181 (2001).
3. Botha, G. J. J., Arber, T. D., Nakariakov, V. M. & Zhugzhda, Y. D. Chromospheric resonances above sunspot umbrae. *Astrophys. J.* **728**, 84 (2011).
4. Snow, B., Botha, G. J. J. & Régnier, S. Chromospheric seismology above sunspot umbrae. *Astron. Astrophys.* **580**, A107 (2015).
5. Felipe, T. Signatures of sunspot oscillations and the case for chromospheric resonances. *Nat. Astron.* https://doi.org/10.1038/s41550-020-1157-5 (2020).
6. Jess, D. B. et al. ROSA: a high-cadence, synchronized multi-camera solar imaging system. *Sol. Phys.* **261**, 363–373 (2010).
7. Jolissaint, L. Synthetic modeling of astronomical closed loop adaptive optics. *J. Eur. Opt. Soc.* **5**, 10055 (2010).
8. Tritschler, A. et al. Daniel K. Inouye solar telescope: high-resolution observing of the dynamic sun. *Astron. Nach.* **337**, 1064–1069 (2016).
9. Felipe, T., Khomenko, E. & Collados, M. Magneto-acoustic waves in sunspots: first results from a new three-dimensional nonlinear magnetohydrodynamic code. *Astrophys. J.* **719**, 357–377 (2010).
10. Gudiksen, B. V. et al. The stellar atmosphere simulation code Bifrost: code description and validation. *Astron. Astrophys.* **531**, A154 (2011).
11. Steiner, O. et al. First local helioseismic experiments with CO[5]BOLD. *Astron. Nach.* **328**, 323–328 (2007).
12. Vögler, A. et al. Simulations of magneto-convection in the solar photosphere: equations, methods, and results of the MURaM code. *Astron. Astrophys.* **429**, 335–351 (2005).
13. Johnston, C. D., Hood, A. W., Cargill, P. J. & De Moortel, I. A new approach for modelling chromospheric evaporation in response to enhanced coronal heating. I. The method. *Astron. Astrophys.* **597**, A81 (2017).
14. Johnston, C. D. et al. Modelling the solar transition region using an adaptive conduction method. *Astron. Astrophys.* **635**, A168 (2020).

15. Mauas, P. J. D. et al. Helium line formation and abundance in a solar active region. *Astrophys. J.* **619**, 604–612 (2005).
16. Ogawa, H. & Fujiwara, T. Analyses of three shock interactions in magnetohydrodynamics: aligned-field case. *Phys. Plasmas* **3**, 2924–2938 (1996).
17. Delmont, P., Keppens, R. & van der Holst, B. An exact Riemann-solver-based solution for regular shock refraction. *J. Fluid Mech.* **627**, 33–53 (2009).

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Author contributions
D.B.J. designed the observational instrumentation setup and acquired the observations. D.B.J. and M.S. performed analysis of the observations utilized in the present study. B.S. designed and carried out numerical MHD simulations. All authors interpreted the observations and simulations, discussed the results, and commented on the manuscript.

Competing interests
The authors declare no competing interests.

Additional information
Correspondence and requests for materials should be addressed to D.B.J.

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