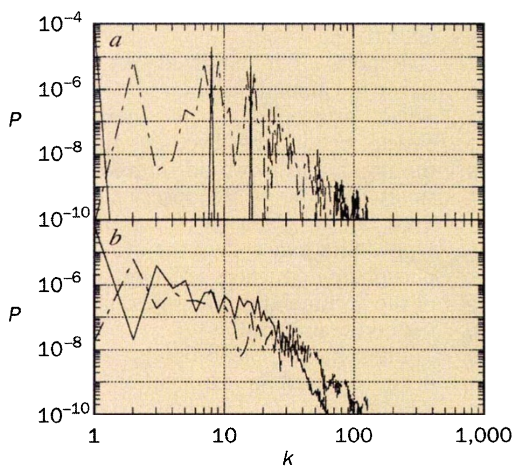

a, Power spectrum of the initial magnetic field (solid) and field magnitude (dot-dash) for a compressible MHD simulation. *b*, Same as *a* but at a later time.

from its original value. (For waves compressed with the plasma, $l \propto 1/\rho$ is maintained.)

The figure (*a*) shows the initial spectrum of a magnetic component of three small-amplitude magnetohydrodynamic (MHD) waves and the corresponding spectrum of the field strength for a one-dimensional MHD simulation to test these ideas. The initial field magnitude spectrum, important in the modulation of energetic particles, is different from the component spectrum, both in that peaks are modulated and thus shifted and in that it is more continuous. The figure (*b*) shows the spectrum after the equivalent of about a day of evolution in the solar wind for modes at *p*-mode frequencies; no higher-wavenumber features remain simply due to steepening and weak nonlinear interaction. The equality of optical and spacecraft higher-frequency *p*-mode observations[1] still poses a problem, but we believe that the case for random coincidences should be re-examined in light of the intermittent nature of the solar-wind turbulence.

Finally, there is no known mechanism for the required *g*- and *p*-mode coupling to any quantity measured by spacecraft. This, in addition to the considerations above, means that the arguments are very strong for a continuum of solar-wind modes with the only preferred basic frequencies corresponding to solar rotation.

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THOMSON *ET AL.* REPLY — We appreciate the remarks by Roberts *et al.*, but disagree with their conclusions. Roberts *et al.* state that the standard paradigm of the solar wind is a turbulently evolving magnetofluid with the consequence that the solar wind has a continuous spectrum. Indeed, time-series variations of the interplanetary magnetic field and of galactic cosmic rays have been studied to gain an understanding of phenomena such as the turbulent propagation of the charged particles[6] and the hypothesized fractal nature of the field configuration[7]. We argue that this 'continuum hypothesis' has never been subjected to a careful statistical test against an alternative theory suggesting that discrete modes were present in the solar wind, because such a possibility had never been considered.

In our paper[1], we stated explicitly "We take as our null hypothesis, H_0, the standard assumption that the various time-series considered have a purely continuous spectrum with no discrete components apart from solar rotation." All the tests we reported, as well as many others, had extremely unlikely outcomes under H_0.

Given that spectra of time-series of interplanetary data are commonly computed, why have discrete frequencies not been identified before? The reason is that those making the measurements were expecting continuous spectra, so chose estimation methods appropriate for determining parameters of a continuous spectrum, such as the slope. Most of these estimation methods used a single data window, so only large-amplitude periodic terms would have been detectable. It has frequently been observed that such spectra often have larger peaks than would be reasonably expected from a process with a continuous spectrum. But because the locations of these peaks tended to change between samples, it was believed that they were not the result of an embedded periodic process.

In retrospect, the "unreasonable" statistical behaviour of such spectra is completely understandable in terms of our hypothesis. The spectrum of solar modes is quite dense in both the *p*- and *g*-mode ranges, so the resolution requirements are severe: of the 2,241 theoretical *g*-mode frequencies for $l = 1$ to $l = 6$ inclusive (D. Gough, personal communication), there are 1,071 adjacent frequencies where the beat period exceeds 1 year. A spectrum estimated from a record of a few months' duration will almost certainly contain some frequencies where two (or more) of these unresolved modes are 'in phase' and so will have peaks at those frequencies. At a different time, these modes may be out of phase, while those at some other frequency may be aligned. Thus, such spectra will seem unreasonably variable compared with the variability expected under H_0.

Previous studies used inefficient statistical methods for estimating spectra. For example, of the two studies cited by Roberts *et al.* as not showing "any higher frequency preferred peak[s] near... 5 min period", their ref. 2 used a Blackman and Tukey method, and their ref. 3 used an unwindowed fast Fourier transform. Both methods are badly biased[8] and, in our view, should be avoided[9]. Nonetheless, several of the spectra for solar-wind data acquired at 0.3, 1.0 and 10 AU of ref. 3 of Roberts *et al.* have clear peaks in the millihertz range as well as in the 'intermediate range' of frequencies of Table 4 in our paper[1]. There are many other papers, for example refs 2, 10, in which peaks in the millihertz region are reported.

In support of our hypothesis that solar modes are responsible for these discrete lines, there is very close agreement between the frequencies reported in Table 2 of our paper and theoretical predictions of *g*-mode frequencies[11], as well as some optical measurements[12,13] of possible *g* modes.

To conclude, we believe that it is an observational fact that the solar wind includes many discrete modes. We do not dispute the fact that turbulence effects also occur; as we noted[1], the ions have become turbulent at *p*-mode frequencies at 5 AU, while the electrons have not. The Voyager data show that some discrete frequencies are still identifiable at 10 AU but they appear to be mixed by 20 AU (ref. 14). The analysis of such discrete modes should aid in developing better theories of the solar wind.

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