ON THE FLUCTUATIONS IN THE SOLAR FLUX AT cm-WAVELENGTHS MONITORED ON SMALL AREAS OF THE SUN'S DISK

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ABSTRACT

We discuss the relatively broad spectrum of fluctuations in flux which is observed at cm-wavelengths when tracking a small area on the Sun's disk. The distribution of power P over the frequencies ω of fluctuations can be approximated by a power-law

$$P \sim \omega^{-\alpha} \qquad (1)$$

where $\alpha \simeq 2$; often a continuous "curvature" is superimposed and a "turn-over" frequency is indicated at about $\omega/2\pi \simeq 10^{-3}$ Hz. Considering the phases of different Fourier components of the time series measured, a significant linear correlation is found between phases of neighbouring frequencies.

All these results can be explained most simply by adopting longitudinal sound waves propagating into the transition region, which to a first approximation is characterized by a linear temperature gradient.

Oscillations of solar flux have been investigated at many radio frequencies by a number of authors (Avery, 1976; Kaufmann et al., 1977; Kobrin et al., 1976; Kundu and Alissandrakis, 1975; Tlamicha and Urpo, 1979; Sentman and Shawhan, 1974). In particular, attention was drawn to pronounced oscillation periods which were suggested to have similar duration as the 5 minute oscillation in the optical domain. The results were rather contradictory: Some authors (e.g. Avery, 1976) claim to have found this kind of oscillations, other (Kundu and Alissandrakis, 1975) did not find any. I do not discuss this question here. Another interesting problem is to investigate the composition of the whole spectrum of fluctuations which can be observed by tracking selected regions on the Sun with a telescope of high sensitivity (< 0.1 Jy flux resolution in Effelsberg, Bonn for 1 sec integration time) and good angular resolution (1.3 arc min at 3 cm in Effelsberg). In the time series of 3 cm wavelength flux a rather broad, quasi-continuously distributed spectrum of fluctuations exists.

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Considering the normalized autocorrelation function of the time series, the solar signal shows a much longer coherence scale length than the time series observed with the same receiver system from noise sources other than the Sun (galactic sources, extragalactic sources, noise-tubes). This means that the solar signal deviates significantly from white noise of equal temperature.

The typical amplitude of the solar fluctuations is of the order of 0.5% of the quiet Sun level, or, in terms of brightness temperature, of the order of 60-70 K. The Fourier transform of the autocorrelation function gives the power spectrum, that is the (relative) distribution of power P over the range of fluctuation frequencies ω. From the slope of P ω in the log P vs. log ω representation a spectral index α can be derived, which is of the order of $\alpha \simeq 2$, according to an approximate dependence $P(\omega) \sim \omega^{-\alpha}$. Besides this, often a "turnover" frequency is indicated in the range of about 10^{-3} Hz, and a continuous curvature in the log P vs. log ω representation is visible, caused probably by an exponential term. In the literature it has been pointed out (Biermann, 1946) that the inverse square frequency dependence is also found in analysing the spectral distribution of spatial moving inhomogeneities on the Sun.

The amplitude information obtained from these power spectra is not sufficient for unique interpretation. There are different processes which can lead to fluctuations with the power spectrum just mentioned.

Now, the power spectral analysis neglects the phase information. One can add this important information by means of a simple Fourier analysis of the original time series. The result is that in many cases - at least observing "quiet" regions on the Sun - a characteristic linear correlation exists between the phases of neighbouring fluctuation frequencies.

I will show now that both, amplitude and phase information derived from the time series of flux are most simply explained by adopting a stationary wave field of longitudinal density or sound waves propagating along the line of sight within the antenna beam.

The fluctuations in any case must come from that part of the radiating volume where the optical depth becomes slightly smaller than 1. The bottom layer, that is the lower boundary of the line of sight at 3 cm (about the bottom of the transition zone), where the optical depth is high, contributes only to the quiet level of the measured flux. It should be noted here that the concept of sound waves and their role in heating the upper solar atmosphere is old and has been frequently discussed (Biermann, 1946; Schatzmann, 1949; Schwarzschild, 1948; Stein, 1968; Ulmschneider, 1971; Wentzel, 1977; Benz and Wentzel, 1979). Instead of using a poor model of uniform temperature and sound speed c within the radiating layers, we use a linear increase of c^2, namely $c^2 = c_0^2\ (1 + h/s)$, with height h and the doubling lengths; c_o is the sound speed at the bottom. Considering small scale fluctuations and the linearized set of the hydrodynamic equations, it turns out that different Fourier components of the density disturbances behave differently. The low frequency components do not propagate as proper waves through the temperature gradient, while the higher frequencies do. The limiting frequency is $\omega_1 = c_o/2s$. Below that frequency the waves are reflected and damped out below the level with c_o.

We now tentatively interpret the turning frequency mentioned above to be this limiting frequency. Qualitatively, the result is that s is then of the order of 100-200 km, if c_o is about 10 km/sec according to a temperature at the bottom of 12000-13000 K.

Before discussing further details, we have to see, how the antenna beam averages over the density waves situated within the beam, over an effective length L. It turns out that an incident sound wave of the kind $A \exp(i(\omega t - kh))$ (with $\omega > \omega_1$) gives a measured fluctuation component of flux $\Delta S \sim A/\omega \exp(i(\omega t - \phi))$, with $\phi = (\omega s/c_o) \ln(L/s)$. The square of the amplitude then corresponds to the values of the power spectrum derived from the spectral analysis above; one could argue that, besides the unknown composition of the original amplitude $A = A(\omega)$, the proportionality of $1/\omega^2$ is reproduced by the model. But, what is more important, a linear phase shift is claimed by our model, in accordance with the observational result. Since $d\phi/d\omega$ can be derived from the Fourier analysis, we now can estimate, in combination with the information on s, the effective length L to be of the order $L \simeq 3$ to 4 s.

Finally, I'd like to say a few words on the dissipation rate of soundwaves along the length L. As I mentioned, often an exponential term in the slope of the power spectrum becomes visible. If we interpret this as being caused by viscous damping of the waves, this term is $\sim \exp(-\gamma\ \omega^2)$ the factor γ being a function of the collision frequency. Up to now, this exponential term could not be determined with sufficent precision. It seems that a typical sound wave in the range of 1 minute period is damped by a loss of 10 to 20% over length L.

In the model proposed, proper shock waves have not been considered, although certainly parts of the sound waves will be changed to shock waves. But, in trying to interpret the measurements, only quasi-stationary wave fields are relevant. Sporadic effects would disturb and shorten the coherence length of the autocorrelation function and, indeed, we have found this in the time series received from slightly active regions.

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DISCUSSION

Wentzel: The computations on the transmission of sound waves are fine for an exceedingly thin transition zone, but the assumption of plane stratification can yield qualitatively wrong answers when the "plane stratification" extends only over a width similar to its thickness, or is time dependent.

Hirth: The local wave approximation is adequate. The horizontal dimension of the observed plasma volume is much larger than the vertical one.

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