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SOLAR SPECKLE INTERFEROMETRY

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ABSTRACT

The technique of speckle interferometry has been applied to solar photographs. Spatial frequencies as high as 4 cycles per arc second have been detected in sunspots.
Subject headings: faculae, solar — granules, solar — image processing — sunspots

I. INTRODUCTION

Labeyrie (1970) showed that suitable analysis of the fine structure (speckle) within stellar images formed by large telescopes yields information about spatial frequencies in the source approaching the theoretical diffraction limit of the telescope. Gezari, Labeyrie, and Stachnik (1972) used this technique to determine the diameter of seven stars and to resolve two close binaries with the 508-cm Hale telescope. The theory of the technique has been developed by Korff, Dryden, and Miller (1972), Linfoot and Witcomb (1972), and Dainty (1973) and will not be discussed here.

To apply the technique in practice requires recording the two-dimensional image in a time interval short compared with seeing changes ($\lesssim$20 ms). In accord with the sampling theorem, the size of the sample elements should be no larger than half the size of the smallest expected feature in the speckle pattern. To ensure adequate temporal coherence in the image so that path-length variations of a few wavelengths can be ignored, a narrow passband ($\lesssim$300 Å) should be employed.

The principles of stellar speckle interferometry apply to images of details within extended sources—specifically, solar features. This *Letter* reports our preliminary efforts to analyze the speckle pattern present on photographs obtained with a large solar telescope.

II. OBSERVATIONS

During good seeing conditions in 1972 April, June, and July, we obtained sequences of photographs of solar features with the McMath solar telescope on Kitt Peak at a rate of 4 s^{-1}. Most of the photographs were taken with a 30 Å bandpass filter centered on 5300 Å. A few were made with a 15 Å filter centered on 3840 Å. Kodak Recordak 35-mm film type 5460 was used with exposure times of 1 to 20 ms. The main telescope (aperture 1.5 m) has a spatial frequency cutoff at 13 cycles per arc sec. at 5300 Å. A few photographs were taken with an auxiliary telescope with a cutoff frequency of 6 cycles per arc sec. With the optical systems we used, the film has a modulation transfer function value of 90 percent at the telescope cutoff frequency (Kodak 1970) and an equivalent rms intensity noise of $\pm$1.7 percent in a single sample element with a size corresponding to twice the telescope cutoff frequency.

The speckle pattern of solar features is manifested as a fragmentation of the image into numerous segments (fig. 1*a* [pl. L8]). Small, high-contrast features such as umbral dots and faculae near the limb show the speckling most clearly, but the fragmentation can be easily recognized in penumbral filaments and granulation and

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PLATE L8

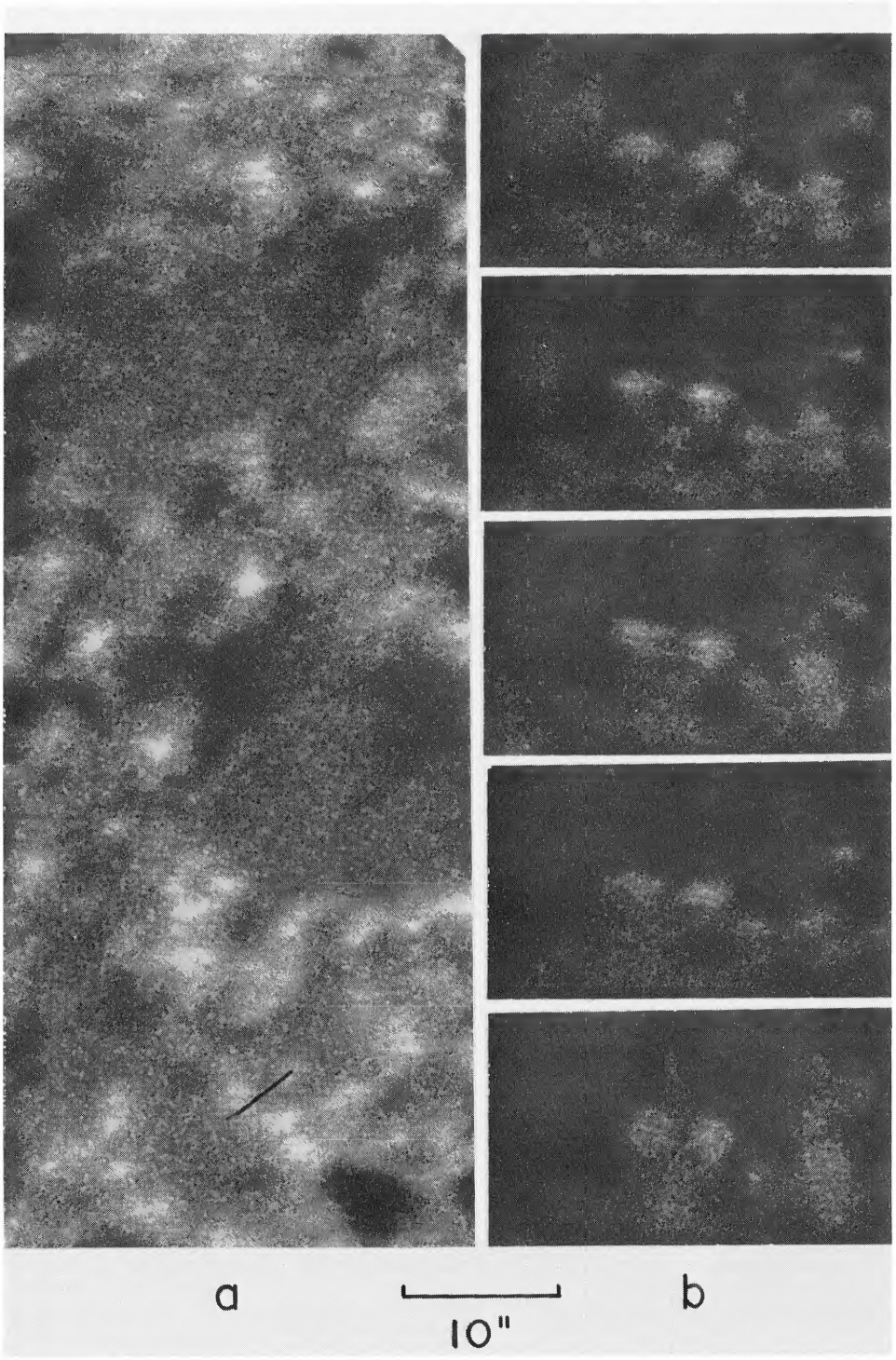


FIG. 1.—Faculae at $\mu = 0.4$ photographed with a 76-cm aperture at $\lambda = 3840$ Å. (*a*) Images of the faculae are fragmented or "speckled." (*b*) Frames taken at $\frac{1}{4}$ s intervals showing the large-scale speckle pattern tends to behave similarly for closely adjacent faculae.

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we have seen it visually in prominences. The course features in the speckle pattern of isolated faculae separated by less than 5″–10″ frequently tend to be identical while more separated features have different patterns (fig. 1*b* [pl. L9]). This suggests that the size of the isoplanatic patch is limited by atmospheric seeing to less than 10″. The fragmentation of solar images has long been noted (cf. Rösch 1956) as a doubling or tripling of images formed with small telescopes. What is new is the appreciation that information about spatial frequencies approaching the diffraction limit of the telescope is contained in the fragmented images.

To analyze the spatial frequency content of the photographs, we selected small areas on the negatives and produced two-dimensional spatial power spectra of these areas by coherent optical processing and also by digital scanning and computer processing. The former technique has been less successful owing to problems of apodizing the edge of the selected area on the photographs. This has to be done with great care for images of extended objects; otherwise, false power is introduced which masks the rather weak desired signal.

Our best results are obtained by scanning the negatives with a digital microdensitometer. An array of densities such as shown in figure 2*a* (plate L00) is converted to intensity, the large average signal is subtracted and the edges of the resulting array are numerically apodized with a cosine bell function as suggested by Bingham, Godfrey, and Tukey (1967). A two-dimensional power spectrum is computed and displayed as an intensity plot (fig. 2*b* [pl. L00]. To improve the signal-to-noise ratio, we add several power spectra together from images obtained within a few seconds of time.

We have recorded the power spectrum of the Moon's limb during a partial solar eclipse in an effort to calibrate our solar observations. Seeing is too variable to allow us to use the results of this observation as a universal calibration. For the present we are restricted to estimates of the high-frequency cutoff of various solar features. Quantitative measures of the magnitude of the power spectrum at various spatial frequencies require development of a suitable calibration technique.

III. RESULTS

Table 1 summarizes our estimates of definite and possible maximum spatial frequencies in various solar features. In the cases of elongated features (granulation and faculae near the limb and a sunspot penumbra), the power spectra are quite asymmetric, so maximum and minimum dimensions are given. For features observed near the limb, the highest spatial frequencies were found in the direction radial to the limb. Except in the case of faculae, the power spectra rather gradually merge into the noise due to film granularity at high spatial frequencies. Thus the results of table 1 are lower limits to the actual highest spatial frequencies present in these

TABLE 1

MAXIMUM SPATIAL FREQUENCIES IN SOLAR FEATURES

Object (λ 5300 Å)	Certain (cycles per arc sec)	Possible (cycles per arc sec)
Granulation ($\mu = 1$)	1.4	2.7
Granulation ($\mu = 1$, $\lambda = 3840$ Å)	0.7	2.2
Granulation ($\mu = 0.22$)	2.2×0.8	2.6×1.1
Faculae ($\mu = 0.22$)	2.8×1.7	2.8×1.7
Penumbral filaments	2.5×1.0	3.5×2.2
Umbral dots	2.6	4.0

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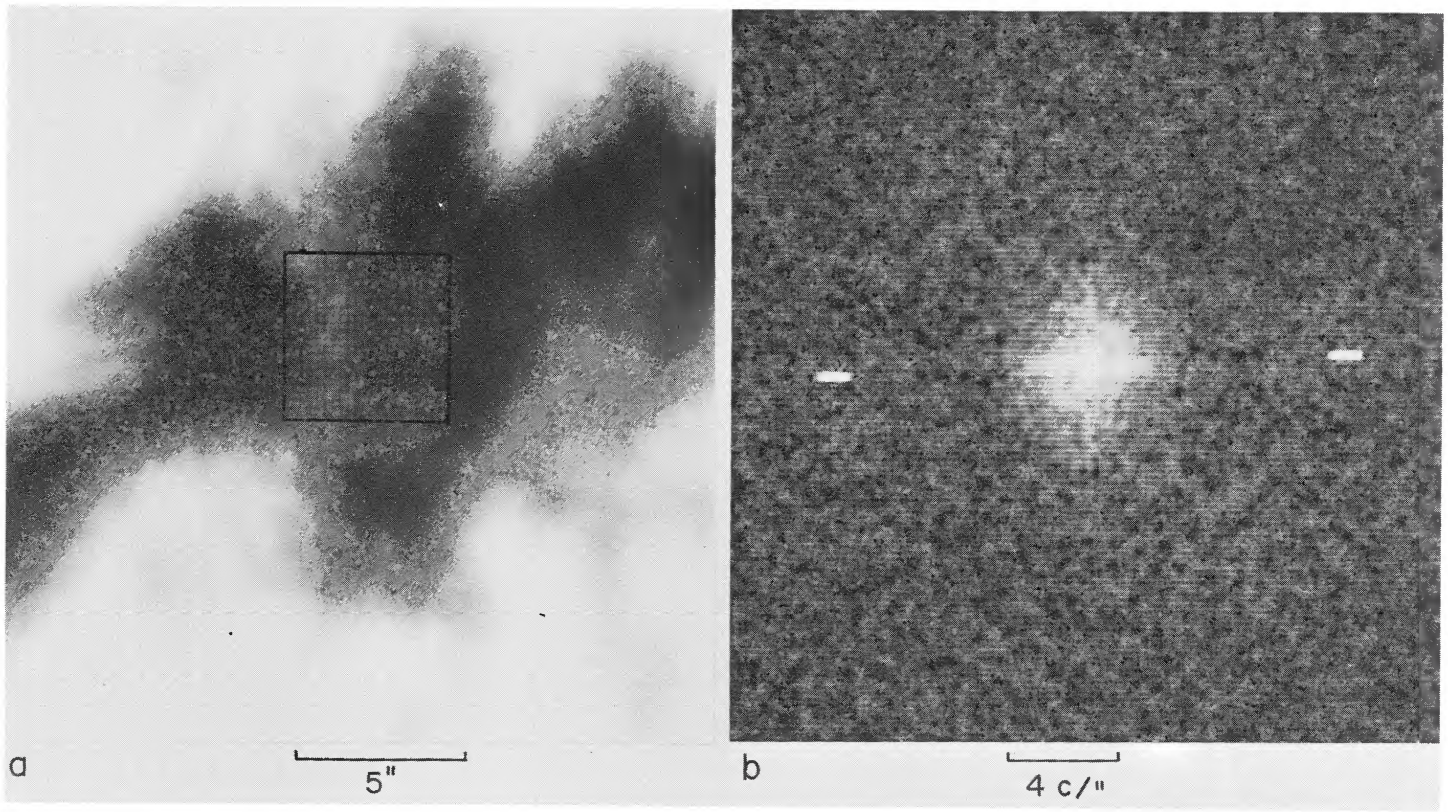


FIG. 2.—(*a*) Umbra of a sunspot. The square indicates the area scanned to produce the power spectrum shown in (*b*). The power spectrum is displayed on a logarithmic scale and shows umbral dots contain significant power at spatial frequencies of 3–4 cycles per arc second.

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PLATE L9

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features. Observations with lower noise will undoubtedly increase these numbers. Since our results are statistical in nature, rare, isolated features of very small size may exist which would escape detection by interferometry at our present noise level.

IV. DISCUSSION

Our results are in good accord with observations of solar features using a Michelson stellar interferometer (Harvey 1972). On the basis of physical considerations of radiative, magnetic and hydrodynamic processes, Newkirk (1972) estimated characteristic sizes of solar phenomena which also agree reasonably well with the present results.

The umbral dots are the smallest structures we have yet observed. Expressed as a length or characteristic scale, the spatial frequency of 4 cycles per arc second is equivalent to 180 km, which is very close to the diameter estimate of Beckers and Schröter (1968) based on the color of umbral dots. Danielson and Tomasko (1971) have also estimated a diameter of 180 km for umbral dots based on digital processing of Stratoscope photographs.

As a result of this work it appears that minimal resolution of small solar features requires a telescope aperture of at least 45 cm while good resolution requires an aperture twice as large.

Speckle interferometry is potentially more powerful than two-aperture Michelson stellar interferometry because the entire aperture is used. This provides more light, and all spatial frequencies are recorded simultaneously. However, the lack of a reference source is a severe limitation for this technique, for it may limit the measurement of a spatial power spectrum. In spite of this limitation, we believe that speckle interferometric techniques are an effective way of obtaining information about small solar features without the problems of lifting large telescopes above the Earth's atmosphere.

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