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E. N. Frazier

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THE QUIET SUN

The photosphere – magnetic and dynamic state

By E. N. Frazier
Space Physics Laboratory, The Aerospace Corporation, Los Angeles, California, U.S.A.

[Plates 1 and 2]

The photosphere is essentially a relatively thin boundary layer between two fundamentally different plasma regimes. The solar interior is characterized by high density, high opacity, high β and convective instability, whereas the outer solar atmosphere has the opposite properties. The convection in the interior provides the ultimate driving force for all of the dynamic and magnetic structure of the solar atmosphere, yet when we view the photosphere, we can observe only the upper boundary of the convection zone. Instead, we observe primarily its various after-effects: overshoot, wave propagation, and confinement of the magnetic field.

These observable phenomena are described with a view toward diagnosing the essential physics above and below the photosphere. The convective modes, granulation and supergranulation, are reviewed briefly; the oscillatory modes are discussed in somewhat more detail. Finally, the magnetic structure of the photosphere is described.

This paper will be a rather general and a rather descriptive talk covering the most fundamental phenomena of the entire solar atmosphere – the convection zone and its various immediate effects. I prefer not to try to develop any particular idea in any great detail in the limited time available. Rather, I would like to stimulate as much thinking and discussion as possible by critically reviewing recent progress and problems in fairly broad terms. I will avoid discussing active regions or chromospheric dynamics and devote the entirety of my paper to truly quiet photospheric phenomena.

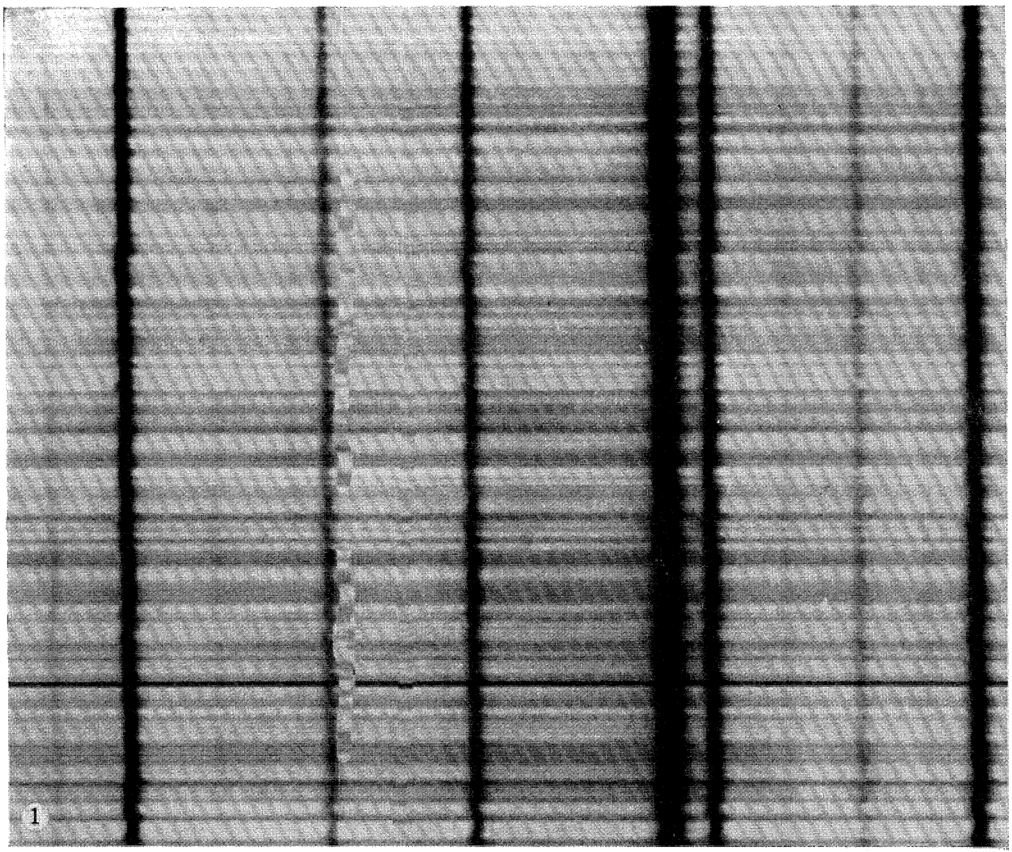
1. Convective modes

The usual starting point for any discussion of this kind is with the smallest, simplest and most familiar example of convection – the granulation. When we look at granulation, we are essentially looking at the 'cloud tops' of turbulent convection. We know that there is a zone of convection in the sun extending to very great depths. In particular, there is a very thin layer, lying just a few scale heights below the photosphere, where the convection is very intense, due to the recombination of hydrogen. Yet, right at the surface, where the energy can finally escape by radiation, then of course the radiative temperature gradient also drops, and the convection is quenched. So we must content ourselves with being able to observe only the upper surface of this convection.

We can essentially measure the size, temperature excess and velocity of these surface elements. The size and temperature measurements are simply taken from white light photographs of the granulation; the velocities are measured from the Doppler shifts of the Fraunhofer lines. Figure 1, plate 1, is a high (spatial) resolution spectrogram of a quiet region. As the entrance slit cuts across successive granules, the alternate bright and dark continuum 'threads' are produced. One can see that, as the absorption lines cross the threads, they exhibit Doppler shifts that are well correlated with the continuum fluctuations. Thus, one can measure convective velocities and their correlation and phase relation with the temperature fluctuations. Such direct measurements yield the following gross properties of the granulation: The mean intercell distance is about 1500 km, or about 10 scale heights, the mean temperature fluctuation is several hundred kelvins (r.m.s.), and the velocities are about 0.5 km/s (r.m.s.), and slightly over 2 km/s peak to peak. The mean lifetime of a cell is about 10 min. All these properties, except perhaps for the mean lifetime, are very sensitive to the spatial resolution, i.e. to the seeing. Since the seeing is essentially unpredictable from instant to instant and extremely difficult to measure, these properties are subject to correction factors which are largely unknown. It seems most likely that these correction factors lie in the range from 10 to 100 %, but even this statement is little more than an educated guess. Measurements of microturbulence provide an estimate of r.m.s. velocities which is relatively free of seeing effects, but these estimates must be used with great caution, because it is not known if microturbulence is even caused by convection. It could be caused, for example, by acoustic waves of very small wavelength.

There is another convective mode present on the Sun. It is not visible in white light because the temperature fluctuations associated with it are too small. For this reason it was not detected until a little over 10 years ago when techniques for observing velocity patterns were developed (Leighton, Noyes & Simon 1962). One can make, photographically, a map of the Doppler shifts across the surface of the Sun. Such a photographic map could best be called a 'dopplergram'. If one adds up 2 or more dopplergrams separated by several minutes, one obtains another dopplergram wherein the short-lived Doppler shifts are integrated out and only the long-lived Doppler shifts are visible. Figure 2, plate 1, shows the striking pattern that results. The fact that the pattern is not visible in the centre of the disk means that the flow pattern consists primarily of the horizontal velocities characteristic of convection at an upper boundary. These cells are very long-lived (about a day) and some 20 times larger than the granulation. For this reason this mode was named, in true American style, the supergranulation. In a classic series of papers (Leighton *et al.* 1962; Simon & Leighton 1964), it was shown that it is this horizontal flow of the supergranulation that distributes the magnetic field and the associated photospheric and chromospheric emission into a coarse, roughly polygonal network. We shall return to this network later in the paper.

When we attempt to combine observational knowledge of the convection zone with our theoretical ideas of it, we find a few new insights but relatively little real progress. The properties of the granulation agree fairly well with the predictions of the mixing length theory, originally developed by Vitense (1953) and since modified, adjusted and manipulated by a large number of authors. Yet the data are not accurate or comprehensive enough to set the parameters of the theory, or even to test how accurate or valid the theory is. The discovery of the supergranulation dramatized the inadequacy of one of the major simplifying assumptions used in convection zone theory; the Boussinesq approximation. In this approximation, it is assumed that the scale height of the fluid is much greater than the characteristic dimensions of the convection itself, yet in the case of the supergranulation, the situation is exactly the opposite. This fact inspired Simon & Weiss (1968) to explore the simpler aspects of convection in a stratified fluid, but their pioneering effort does not seem to have generated any continuing or more detailed work on this problem. In fact, their tentative prediction of a third convective mode in the Sun has not been conclusively tested. The idea of such a mode, the so-called 'giant cells', has been around for some time



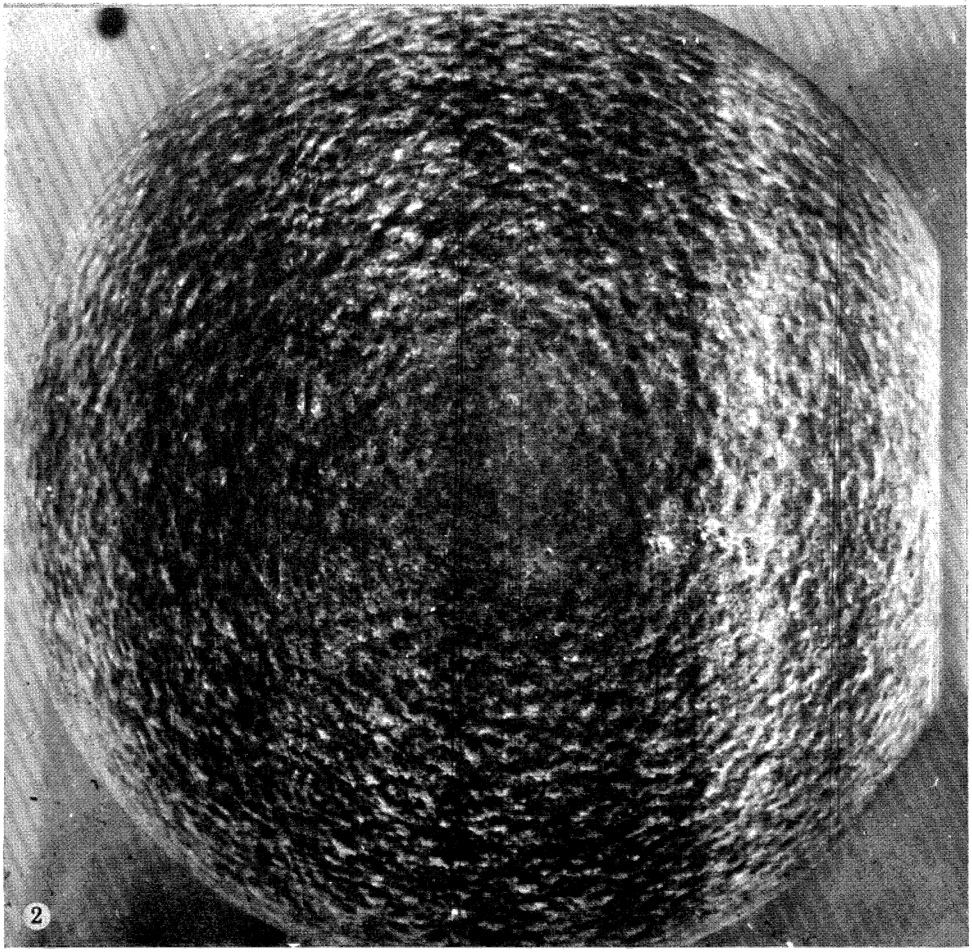


FIGURE 1. Example of a 'wiggly line' spectrogram. Wavelength increases to the right. The temperature fluctuations of the granulation, as evidenced by the bright and dark continuum streaks, can be compared with the doppler shifts of the absorption lines. Spectrogram courtesy of Kitt Peak National Observatory.

FIGURE 2. A full disk 'doppler sum' velocity spectroheliogram. When two velocity spectroheliograms taken 2.5 min apart are photographically added, the effects of the 5 min oscillations are largely cancelled out and the supergranulation flow pattern becomes clearly visible. This spectroheliogram made by D. K. Lynch at the San Fernando Observatory.

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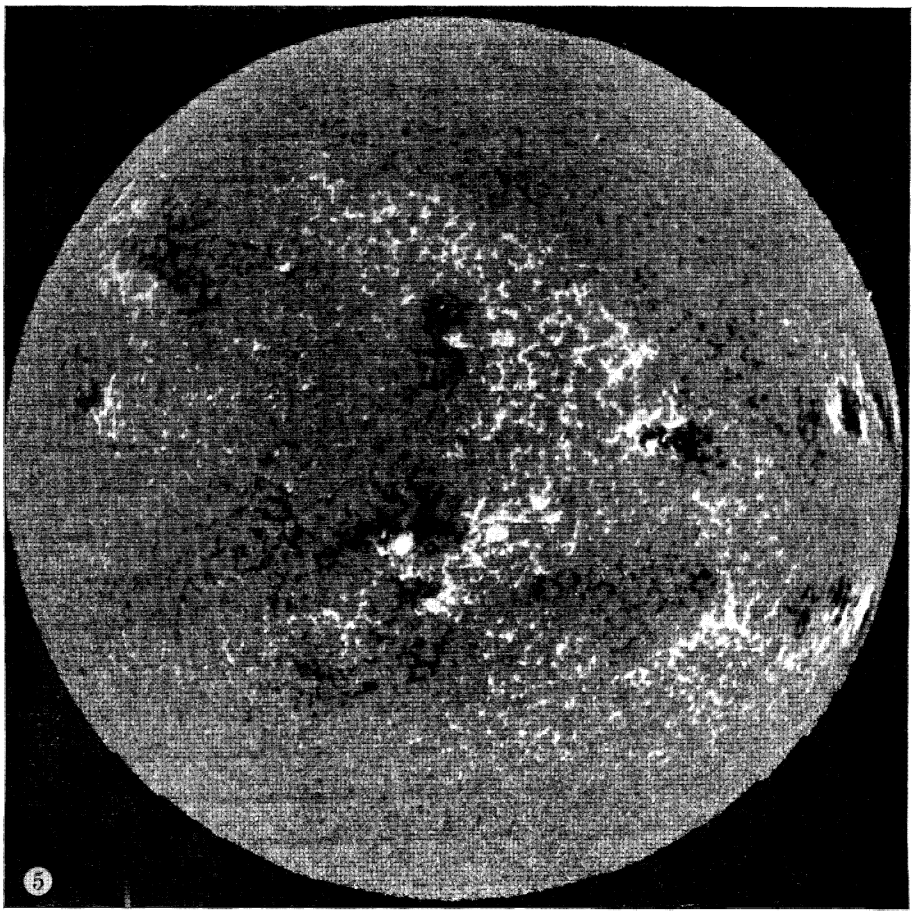

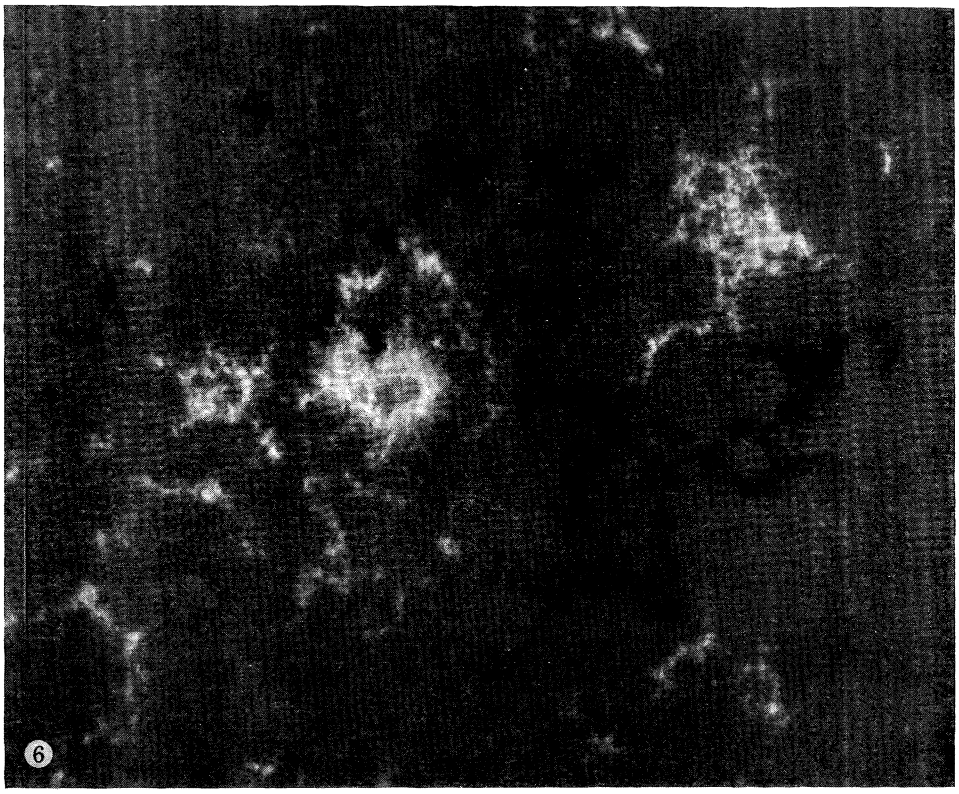

Figure 5. Full disk magnetogram. This particular example is an excellent illustration of the dispersal of magnetic field elements into a coarse network pattern. Courtesy of Kitt Peak National Observatory.

Figure 6. High resolution magnetogram of an active region and surrounding network structure. Network and plage magnetic fields are further fragmented into clumps which are seen to be roughly the size of the granulation. Since direct magnetograms are still unable to resolve these clumps, their true size could be much smaller. Magnetogram made by G. A. Chapman at the San Fernando Observatory.

(cf. Bumba 1967), but this mode is so large, and its observable effect is so subtle that no one has been able to show conclusively whether it even exists or not!

One aspect of the convection problem where one could expect a fruitful interaction between theory and observation is the study of convective overshoot. However, the theory seems to be immensely complicated and the observations are certainly very difficult and seeing-dependent. Some beginnings, mostly phenomenological, have been made on this subject (cf. Moore 1967; Musman 1972), but at present it is still largely an unexplored area. In summary, it must be said that what we know about the structure of the convection zone today is still based almost exclusively on theoretical models which are direct descendants of the mixing length theory.

So, despite the fundamental place of the convection zone in the whole scheme of things, our knowledge of it is really very meagre. We must now look for more indirect data to provide information. We seek tracers, or messengers, from the convection zone. There are two known now, and I am sure that more will be discovered as time goes on. These tracers can be studied from two different points of view. First, they are valuable as diagnostic tools for further probing of the convection zone. Secondly, they are valuable in and of themselves because they produce directly the visible phenomena of the chromosphere and corona. As we shall see, it is sometimes difficult and probably unwise to separate these two points of view.

The two tracers I refer to are of course the 5 min oscillations and the magnetic field. We will discuss the oscillations first.

2. Oscillatory modes

The oscillations were discovered at about the same time the supergranules were when it was realized that a third, fundamentally different component was present in the Doppler shifts. This component was intermediate in size between the granulation and the supergranulation and most importantly exhibited oscillatory behaviour with a period of about 5 min. This discovery came as a surprise at the time, but when someone finally tells you that there is oscillatory phenomena in the photosphere, then it is fairly easy to show that wave motion of various types can be generated in the convection zone and that the overlying photosphere is capable of propagating a wide variety of waves. So the situation in the photosphere is crudely analogous to a pot of boiling water covered with a thin layer of Jello.

Figure 3 is a good example of the velocity data one has to work with when analysing the oscillations.

The task now is to develop a theory that explains the propagation of these waves. The hope is that once we understand the propagation of these waves we will not only be able to predict how these waves dissipate and heat the atmosphere, we will also be able to identify the generation mechanism and thus infer properties of the convection zone from the observed wave characteristics. The problem is that there are too many theories available; there are several different mechanisms in the atmosphere that can produce a resonance at 5 min. So the first task is to identify which theory is the correct one.

It quickly became accepted that the meeting ground between theory and observation, the testing ground for different theories, is the k–ω plane, or diagnostic diagram. The data can be represented in this plane by a fairly straightforward two dimensional Fourier transformation (horizontal wavenumber and frequency). The theoretical representation is simply a plot of the roots of the dispersion equation, which is derived from the equations of motion by a linear harmonic analysis. Figure 4 shows what the diagnostic diagram looks like for the solar

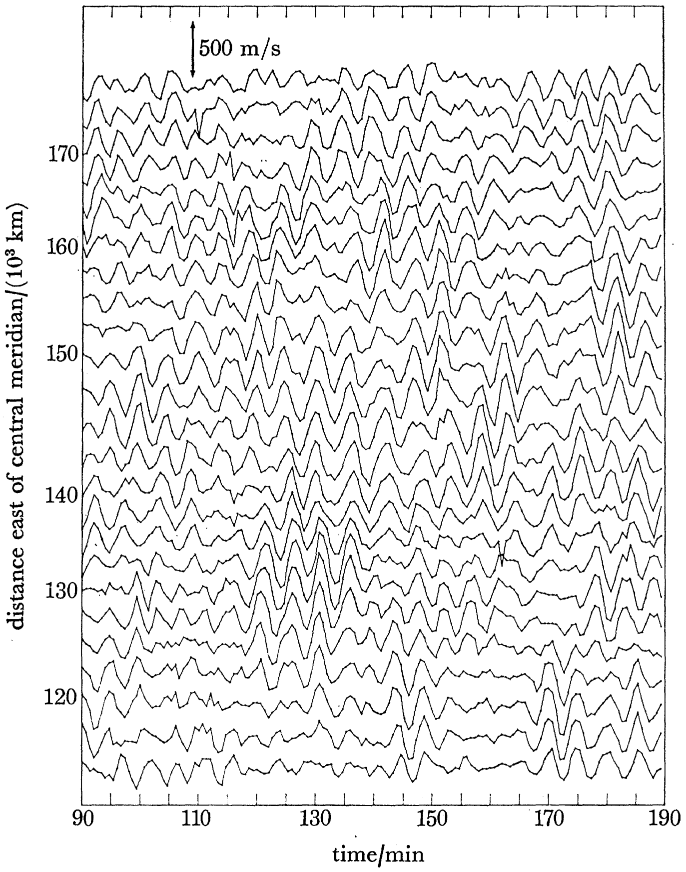

FIGURE 3. Example of time traces showing the 5 min oscillations. The curves represent velocity as a function of time at points separated by 2500 km. (From Howard, Tanenbaum & Wilcox 1968.)

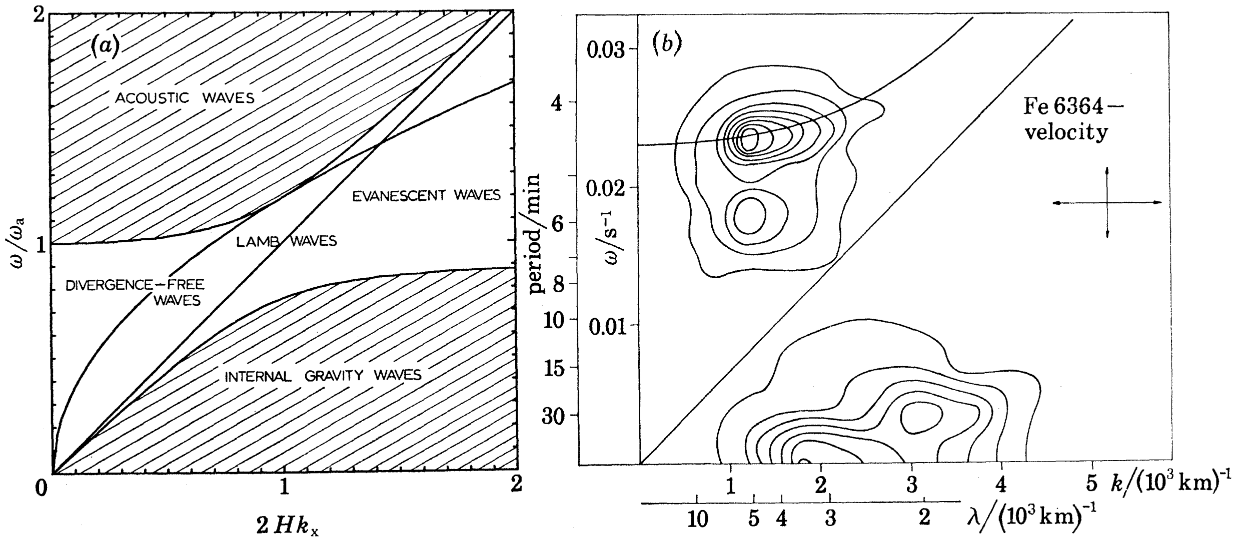

FIGURE 4. The diagnostic diagram, or k–ω plane as seen by theoreticians and by observers. (*a*) Theoretical k–ω plane for the photosphere, showing the location of the various possible oscillatory modes (from Leibacher 1974). (*b*) One example of an observed k–ω plane. The granulation is represented by the low frequency power; the oscillations by the higher frequency power (from Frazier 1968).

atmosphere. Acoustic waves are permitted in the upper left region, and internal gravity waves in the lower right. In addition, Lamb waves (horizontal acoustic waves) are permitted along the locus $\omega = ck$, and surface gravity waves along the locus $\omega k^{\frac{1}{2}}$ in the upper right region. There is a local resonance at ω_{a}, the gravity cutoff to acoustic waves. Furthermore, due to the stratification of the atmosphere, there are a number of possible non-local resonances, or cavities to trap various modes. I will not go into all the different published models here. An example of the diagnostic diagram as derived from observations is shown in figure 4*b*.

The diagnostic diagram has been explored by many people, both observationally and theoretically for more than five years now. Stein & Leibacher (1974) present a good review of this exploration. A fairly steady stream of papers has been emitted and what has been learned? It has been learned that the waves in question are gravity modified acoustic waves, that the resonance is intimately associated with the gravity cutoff, and not much else. There are still several mechanisms that can produce a resonance at that general location in the k–ω plane, and they have not been distinguished yet. We seem unable to proceed to a detailed study of the generation and dissipation processes. To put it harshly, research on the oscillations has been drifting aimlessly in the k–ω plane for some time now.

Why is there this lack of progress? It seems to me that there are two possible explanations. One possibility is that sufficient resolution in the k–ω plane has not yet been achieved. Such a situation would exist if the various wave fronts of the different oscillations were so badly superposed on each other that the surface of the photosphere would simply present a very ‘choppy’ appearance. In a case such as this, the resolution of the different wave fronts and the measurement of wavelengths and frequencies requires a great deal of careful effort. The requirements of this careful effort can be expressed more explicitly in terms of a minimum resolution in the k–ω plane and minimum statistical stability.

If you know these minimum ‘Fourier requirements’, it is simple to calculate the minimum observational parameters you need, such as field of view, total time span of observation, number of data points, etc. But in order to know the minimum ‘Fourier requirements’, you first need a theoretical model which makes fairly explicit predictions in the k–ω plane. The minimum requirements are then whatever is necessary to test that particular model. One such example is the model of Ulrich (1970) which predicts a pair (or more) of curved resonance lines in the k–ω plane, the first line being the fundamental, the second line being the first overtone, etc. Here one can calculate what is needed to detect the curvature and separation of these resonance lines. In fact a student of Ulrich is working on this at the present time and, based on these simple calculations, he feels certain that he can conduct an unambiguous test of at least this one model. Looking back over previous efforts though (including my own) it must be said that although they have been sophisticated and impressive efforts from the standpoint of an observational astronomer, they have been inadequate from the standpoint of the k–ω plane. In all fairness, they have been inadequate because of very real practical restrictions such as seeing conditions or computer speed and memory size. But it is a possibility that the k–ω plane will be a useful tool only when these restrictions are somehow overcome.

The second possible explanation for the lack of progress is that the very use of the k–ω plane is unrealistic; that we have placed too much confidence in Fourier transforms. The oscillations we have seen are *not* perfectly periodic. In the time domain, it has been shown by Cha & White (1973) that the waves come in bursts or wave packets of mean duration 20 min, and that successive bursts are *uncorrelated* with each other. The same effect seems to be true in the space domain also;

the waves seem to occur in non-periodic clumps. Now these effects could be caused by the superposition mentioned above. They could also be caused by the waves still being very close to their sources. If this is the case, then the waves themselves could be very transient in space and time and the harmonic content of the observed motions could easily contain a sizeable contribution from the sources themselves. These source terms could very well be non-periodic and transient. Now, if this is indeed the situation, then comparison with current theoretical predictions on the k–ω plane are useless because the theoretical models are based on a linear harmonic analysis which specifically *excludes* source terms. So what is really needed here is a more realistic theory, which explicitly includes the sources that generate these waves. One can sound a rather optimistic note here, though. If this approach turns out to be the more fruitful one, then one will have established a direct link between the oscillations and the convection, making the oscillations a very direct and effective probe of the convection zone itself.

3. MAGNETIC FIELD

I now wish to turn to the second tracer of the convection zone, the magnetic field. As mentioned earlier, it is the supergranulation which transports the magnetic flux tubes to its boundaries, thereby producing the coarse reticulated network. This is illustrated rather well in figure 5, plate 2, a full disk magnetogram. These flux tubes extend up through the entire atmosphere, producing local heating at every level. Thus this network is traced out by increased emission from the photosphere all the way up through the transition zone, making it one of the most ubiquitous properties of the solar atmosphere. In addition to the local heating, the network is also the location of isolated downdrafts of 50–100 m/s at the photospheric level (Frazier 1970). The flow pattern associated with the chromospheric network has not been thoroughly studied yet.

Now, what do we know about these regions where the magnetic field is clumped? We would like to find out the size, strength and structure of the field. We also want to investigate the dynamic effects; wave propagation, energy dissipation, instabilities, etc. We certainly know they are there. But right now we are just beginning to seriously study questions number one and two, and with very curious results.

The problem is that these magnetic clumps are further fragmented (presumably by the granulation) into features which are smaller than the resolution of current telescopes. Figure 6, plate 2, shows an indication of this fragmentation. Now let us examine the direct evidence of the size of these features. The best evidence so far consists of a single type of picture taken from a single telescope (Dunn & Zirker 1973). That picture is a direct image photograph taken at the Sacramento Peak Observatory Tower telescope. It is taken through an Hα filter tuned to the far wing of Hα, so it shows the local heating produced by the magnetic field in the upper photosphere. In this type of photograph the fragments are resolved into features significantly smaller than the granules. These fragments are indeed at the edges of the granules, as we would expect. They have a mean size of about 200 km, which is roughly the same as a scale height. This size is also right at the limit of resolution of the largest telescopes, and that resolution can only be achieved on those very rare occasions when atmospheric seeing is at an absolute minimum. The slightest degradation of resolution at any point from the atmosphere through to the detector makes this fine structure undetectable. Note also that this observation does not measure the magnetic field itself, only the heating effect, and since we are not sure of the mechanism by which the magnetic field produces the heating, we are not justified in inferring that the magnetic field elements are equally small. Attempts to measure directly the size of the magnetic field on this scale are extremely difficult and the results so far seem to indicate that the magnetic features are slightly larger (Simon & Zirker 1974). This result is however not completely conclusive. So, directly, we still do not know how small the fields are.

Why this obsession with the small sizes? Why is it so important? It is not really the size that we are after so much as the true field strength, which is inversely proportional to the area of the features. The reason for that statement is that the magnetic field strength observed by virtually every instrument in the world is really mean field strength, averaged over the resolution element, which is sometimes quite large. These apertures are about 2″ square at the smallest, and the observed field strengths range up to about 10 mT (100 G) in quiet regions. Now if the magnetic features are much more concentrated than the resolution element, then the true field strength is greater than the observed field strength by the ratio of the respective areas. And it is the *true field strength* which determines the physics of these flux tubes. For example, consider the energetics of these flux tubes. We can express the energy content of the various components of the photospheric plasma in terms of a magnetic field strength, assuming the magnetic field to be in a state of equipartition of energy with that component. For example, the supergranulation possesses a turbulent energy density equal to a magnetic field of about 2–3 mT. The granulation turbulent energy density corresponds to about 50 mT. The thermal energy of the photospheric plasma itself corresponds to about 150 mT. This is just equivalent to the statement that $\beta = 1$ in the photosphere for a magnetic field of 150 mT. Note however that this last situation could be obtained only if the interior of the flux tube could somehow be totally evacuated. If the true field strengths exceed these values, then we have to find more dynamic mechanisms to maintain these features. As we shall see, we are right now poised at the uppermost limit of these equipartition values.

There is very strong indirect evidence for large values of the true field strength which comes, oddly enough, from the errors and inconsistencies of present magnetographs. In fact, these errors are proving to be almost a richer mine of information than the original data. Most magnetographs place an exit slit on the steepest part of the line profile and measure, not the Zeeman split directly, but the change in *intensity* as the Zeeman split shifts the polarized line profile across the exit slit. The Zeeman split is then *inferred*, after calibrating the slope of the line profile. Such a technique is very sensitive, but is subject to two errors: (1) If the line depth changes in a magnetic region due to localized heating, the line slope will decrease relative to its calibrated value, and the inferred magnetic field will drop below the true average magnetic field value. (2) If the Zeeman split is large enough to shift the sigma component all the way to the exit slit or beyond, the effective slope of the line profile will again decrease (in this case it can even go negative) and the inferred magnetic field will again drop. Now we know that both errors are present. The only thing we do not know is the magnitude of each one.

Both these errors can be detected and measured simply by observing two lines simultaneously which have different responses to temperature and magnetic field. This was first done actually for a totally different reason, and the errors were detected accidentally. Figure 7 shows a simple scatter plot of magnetic field strength measured from two lines simultaneously. If no errors were present, the slope of this scatter plot would be one. Actually, these two particular lines are a poor choice because they differ in both their temperature and magnetic response, so we cannot measure the relative contributions of the two sources of error. However, we can see immediately a very fundamental new fact: *the error is independent of the observed field strength.* Since both sources of error depend on the true field strength, we can conclude that the true field strength does not vary from feature to feature, and that the variations found in the observed field strength merely reflect variations in the fractional area of the resolution element that are filled by the features (Frazier & Stenflo 1972). So we have learned immediately that *there is some very effective equilibrium process in the convection zone that maintains each and every flux tube in the quiet photosphere at the same field strength.*

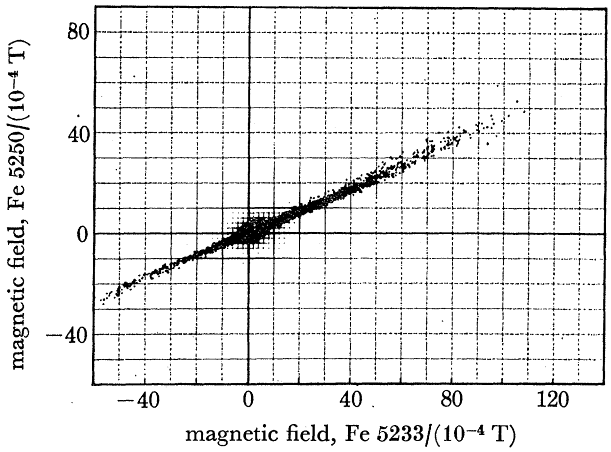

FIGURE 7. Correlation of calibrated magnetic field strengths measured simultaneously in two different photospheric lines. The slope is very nearly $\frac{1}{2}$, indicating an error in the calibration technique which is as large as a factor of 2 and which is independent of the observed field strength. (From Frazier 1970.)

What is the magic value of the field strength? To find that out, we must repeat the experiment with another pair of lines, this time differing only in their Zeeman sensitivity or only in their temperature sensitivity. Also, we must compute a detailed model of these features, including such complexities as a continuous variation of the field strength across the feature (the magic field strength now becomes the peak, or central field strength). It turns out that to get a unique result, the model has to be quite specific, so that temperature profiles, downdraft profiles, etc. have to be included also. One can then compute a predicted average line profile that the magnetograph sees, and from this, the predicted error. The predicted error is then compared with the observed error, and model parameters are adjusted in the classic manner. Owing to the large number of model parameters, we need many observations of different types. This is all quite feasible though, if somewhat tedious.

A first iteration of this analysis technique has been completed by Stenflo (1973). In this analysis a relatively simple model was used and it was fitted to a relatively limited data sample. As a result, one ambiguity remained; the shape of the magnetic profile could not be specified. Yet even with all these caveats, the surprising result was obtained that the peak field strength of these features must lie in the range of 140–230 mT. A second complete iteration of this technique is presently underway by myself and Stenflo, this time with a much broader data base and a much more realistic model. This time we expect to be able to specify a completely unique model. This analysis is still at an early stage, but I would hazard a guess that it will result in a peak field strength of at least 150 mT, and probably about 200 mT. When we know this number for sure, then we can settle down to do some real plasma physics.

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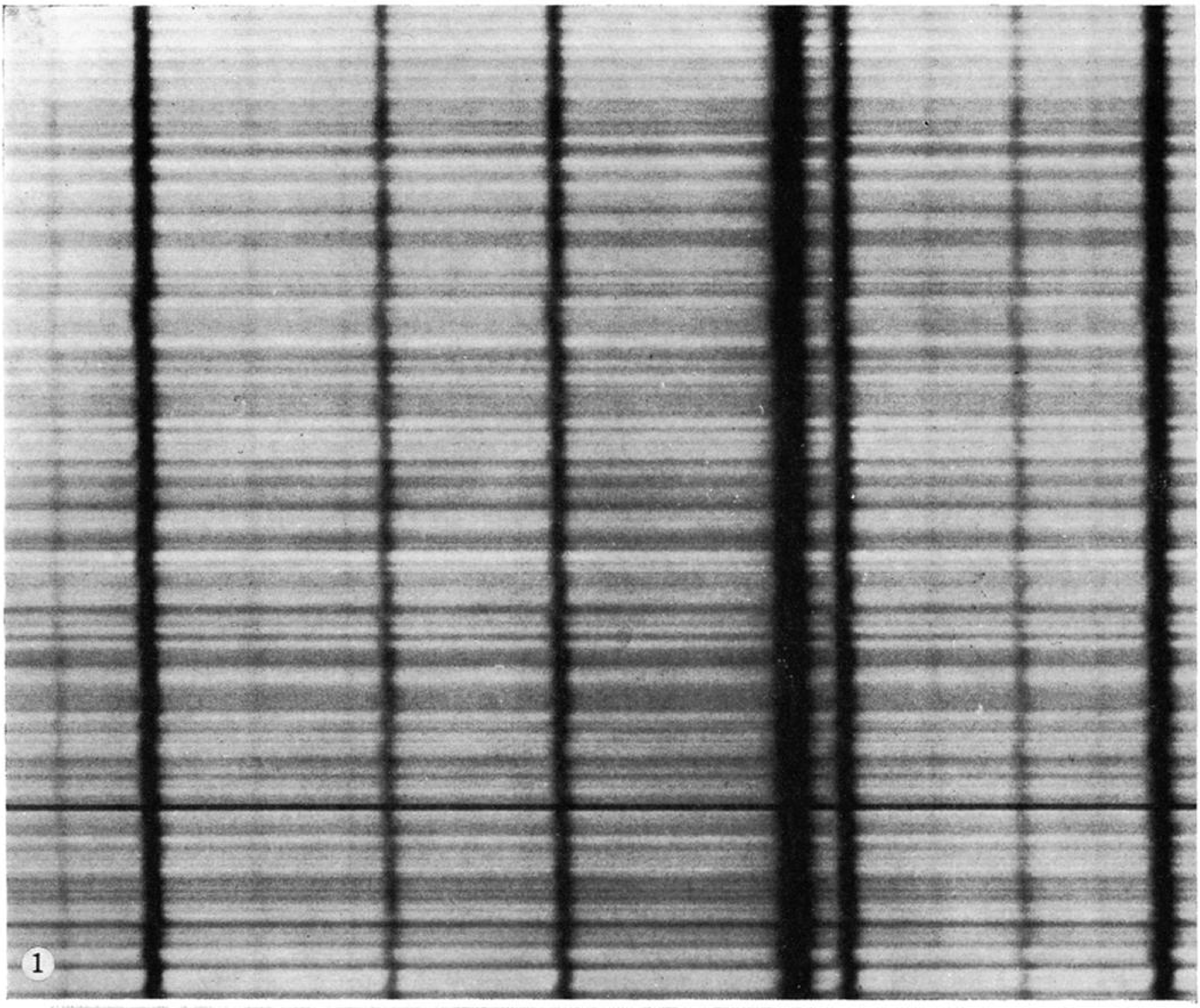

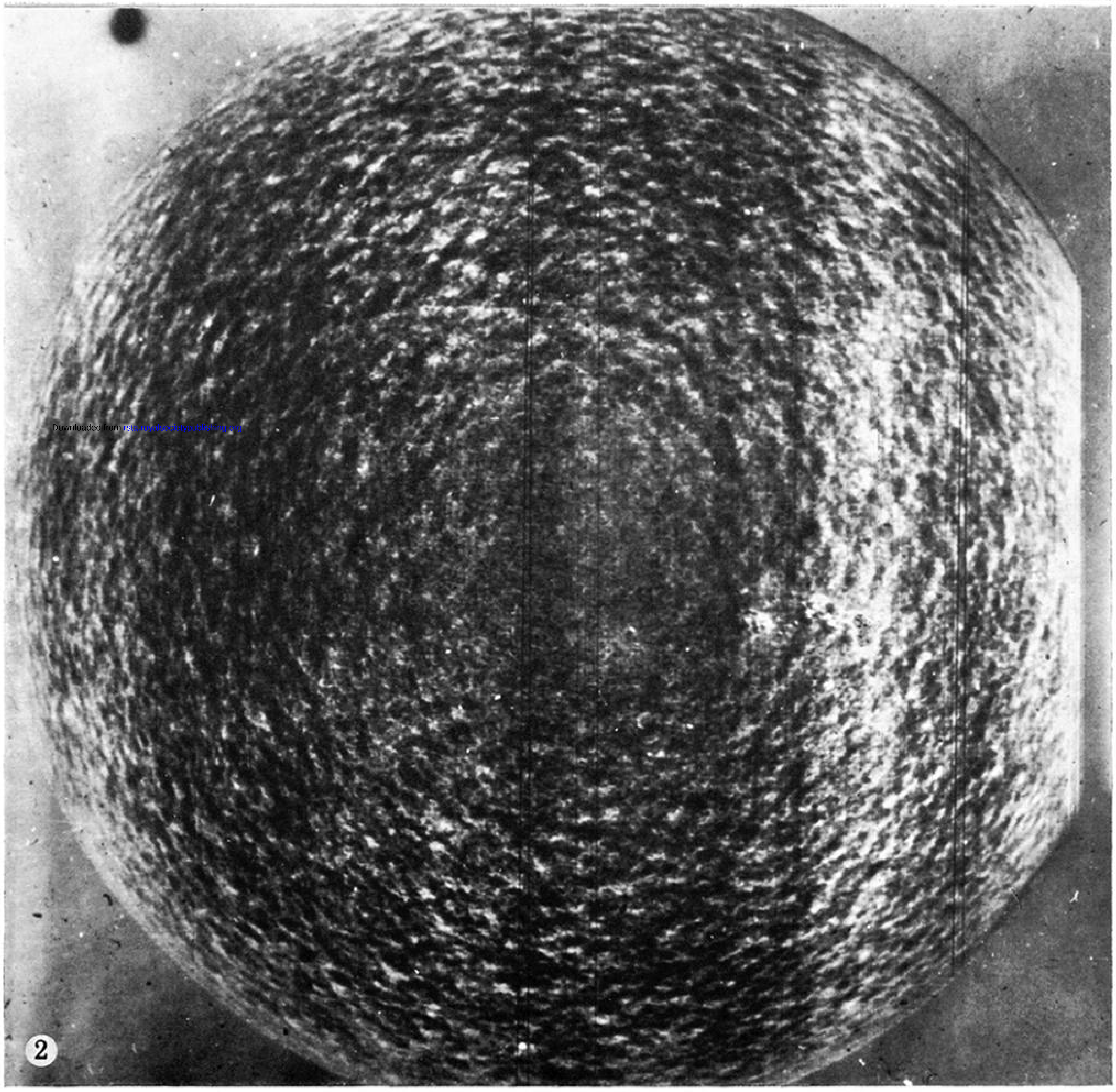

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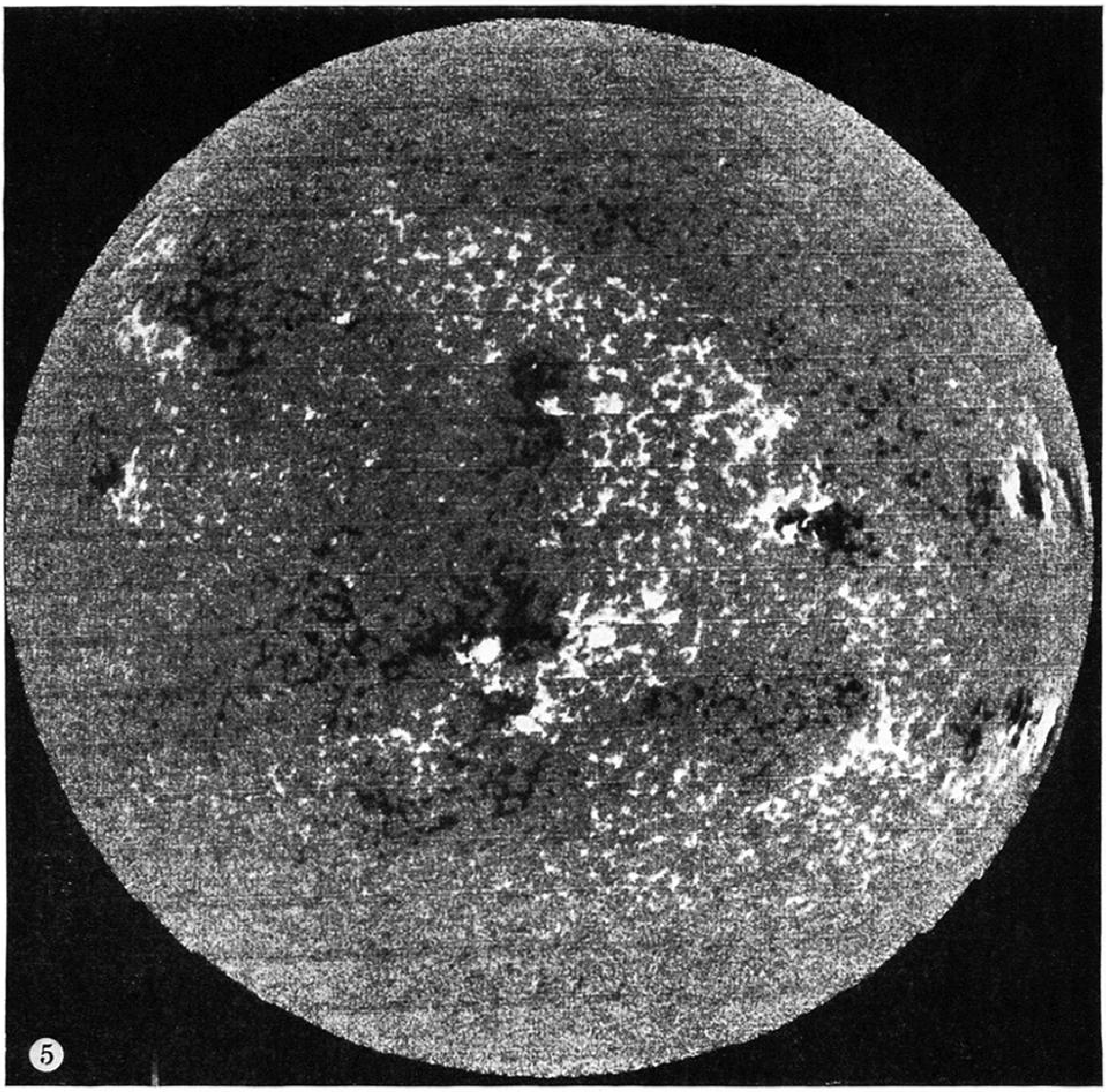

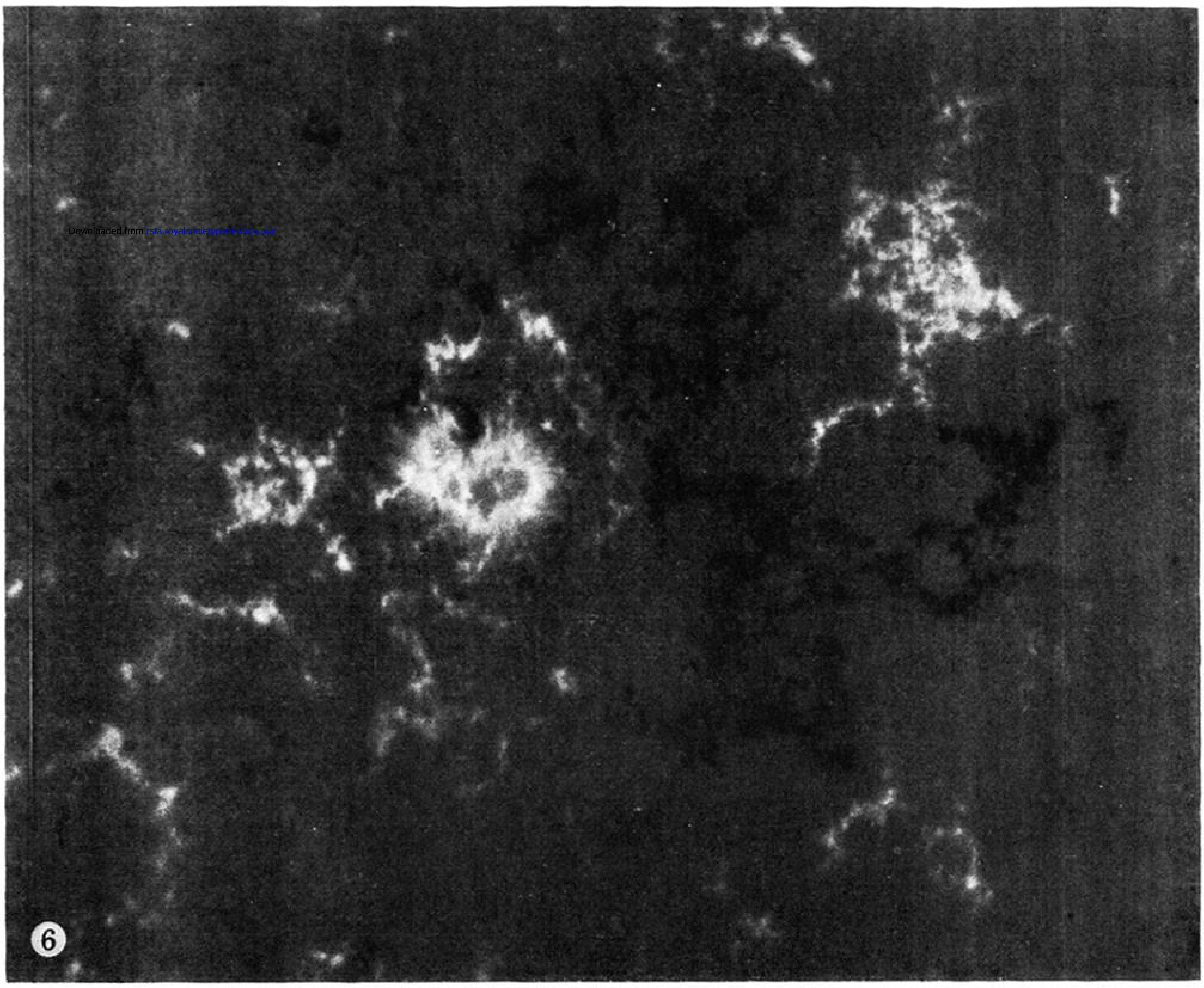

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