ical aspects. The fourth slide shows the kind of detail one can get in the sunspots. In the fourth flight last summer, there was made a particular attempt to follow a sunspot. The fifth slide shows a very large sunspot. DANIELSON has given considerable thought to these structures, in particular trying to explain the filamentary character. I do not have time to go into his theoretical discussion, but he seems to have ruled out all possibilities one could think of or one has thought of anyway, except the possibility that this elongated filamentary structure is produced by convective roles. One feels that the prevailing magnetic field which emerges from the sunspot is horizontal in the region of the penumbra, and that this magnetic field inhibits the convection which would have arisen in the absence of the magnetic field. The inhibition gives rise to a new form of convective motion, which has been studied at least in the incompressible case (convective roles being the cause of this pattern) although I am not at liberty to discuss it now because of time.

— R. B. LEIGHTON:

We have been spending about a week here discussing velocity fields, so I would like to take the liberty of showing you some as they appear on the surface of the sun. Let me first outline briefly the results which our observations have indicated to us. First, we have definite evidence for *horizontal motion* (*i.e.*, tangential to the solar surface) whose magnitude lies somewhere in the range 0.2 to 0.5 km/s, on a scale of about 30 000 km. This size is relatively large compared with the solar granulation. These motions represent relatively steady flow away from centers at which upward moving material arrives at the surface. There is some indication of a correlation with the emission in the K line of calcium. In addition, we find *vertical motions* which have a strong correlation between brightness and direction; namely, bright elements seem to be moving upward on the average—here the velocities are in a range 0.3 to 0.4 km/s and the linear scale is about $3 \cdot 10^3$ km and larger. The lower limit to the size is determined by our resolution—there may well be such motions on a smaller scale. These vertical motions show a strong oscillatory character, with a period of (296 ± 3) s, based upon about 25 observations. The number of oscillations that a given volume element will undergo before the oscillation dies out lies somewhere in the range from 2 to 4.

Now as to the means of observation—this is similar to the scheme devised a few years ago for measuring the magnetic field (R. B. LEIGHTON: *Ap. J.*, 130, 366 (1959))—it is based upon a photographic cancellation procedure in which one simultaneously takes two photographs—(with the spectroheliograph) of the same region of the solar surface and introduces by suitable means a difference between these two photographic images, which difference is a measure of the quantity one wishes to study. We use for the most part a line of Ca I at wavelength 6103 Å, a relatively strong line so that the level in the solar atmosphere to which the measurements refer is certainly something like a scale height above the phosospheric level one sees in integrated light. We also use a line of Fe I at λ 6102 very close to this. This has an excitation potential of about 4.8 eV for the lower state, and so is formed at a considerably lower level in the solar atmosphere. We have also made extensive observations in sodium D_1 at λ 5896. Also, in passing, I mention that we have also made measurements in H_α—these will have to be discussed at a later time. First, I show a slide which illustrates the principle of the method with respect to the magnetic field measurements, because to appreciate what comes later, one should know something of the procedure. We take a pair of photographs with the spectroheliograph—these are obtained by moving a slit slowly past a pair of solar images, formed using a beam splitter. It takes a few minutes to go from one edge of the image to the other. In the case of the magnetic field a quarter wave plate and polaroids are introduced in such a way that one photograph has blocked out of it the left-hand circularly polarized light and the other, the right-hand circularly polarized light. So, the difference between the two images is just what one needs in order to measure the line-of-sight component of the magnetic field. Now, in the case of the magnetic field, after having taken one scan across the image of the sun, we move the plate holder over, reverse the quarter-wave plate (which reverses the sign of the field sensitivity of the two images) and we then scan, in the opposite direction, back across the region we just came over. I mention this because we do a similar thing for the Doppler shift, and it plays an important role in detecting the vertical oscillations. In the case of the magnetic field, both of the images are taken using one edge of the line profile—and the quarter-wave plate and polaroid are introduced in such a manner that there will be a slight difference of intensity on the two images at any point where there is a magnetic field. As you see there isn't very much difference between these two images, and sometimes it takes a sharp eye to see that there is any difference at all. However, with careful photographic procedures, one can make a contact transparency of say, the right-hand pair of these images and develop it exactly to unit gamma in such a way that, if placed upon its own negative, it produces an essentially featureless field.

Now, if one places the contact transparency instead upon the other pair of images, the brightness fluctuations due to, say sunspots (wherever these fluctuations really are due *only* to brightness fluctuation *common* to the two pictures) disappear, whereas the true differences due to the magnetic field are doubled. As a final step we make enlargements of both of these « singly-cancelled » images to exactly the same scale, make a contact transparency of one of them and cancel it against the second one; this then removes the dust streaks which still remain at this stage and results in a « map » of the magnetic field of the region.

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Now, for the Doppler effect we do precisely the same thing except we don't have a quarter-wave plate or a polaroid in the two light beams. We do, however, set the slit of the spectroheliograph on *opposite sides* of the line profile so that a shift in wavelength of the line will introduce an increase in brightness in one image and a corresponding decrease in the brightness of the other. The next slide shows the result of this method applied to an image of the entire sun—if we didn't already know it we would hereby have established that the sun *rotates*, because as you see the image varies smoothly from very bright at one edge, to very dark at the other edge. However, by twisting some knobs on the machine we can « tilt » the spectral lines and remove the part of the signal that is due to the rotation and leave only the signal due to random motions on the surface. The next slide shows the same thing with this having been done. Now here we see the first result that I mentioned earlier, namely, the appearance of what we take to be essentially *horizontal* motions on a large scale. You will notice that there is a « graininess » to the photograph predominantly about halfway from the center to the limb. There is hardly any Doppler signal near the center of the disc and, for other reasons, not much near the limb (because we are looking at such high elevation there and the resolution is not good enough to resolve them). Now look at the « grainy » regions; they are about 30 000 km in diameter, quite large compared with the granulation, but this is definitely a typical size as you can see. You will notice that they are always dark on the side towards the center of the sun and bright on the side away from the center, and they have an elongated shape which we take to be the effect of projection (because of the slanting view near the edge of the sun) upon essentially circular areas. Their absence near the center of the disc indicates that they correspond to *horizontal* motions which can only show up where you see them with a significant component along the line of sight. We believe these to be essentially outward motions, diverging from centers, presumably columnar convection currents, which bring material up from the convection zone, relatively deep underneath the surface, to the surface. You will see these on some of the further slides also. The next slide shows a pair of original images (at a larger scale) whose difference will eventually give us the Doppler pattern over the surface. The reason I show these is that one of the images has essentially *higher contrast* than the other. This is a reproducible characteristic always observed for two such images taken in the light of the calcium line λ 6103. We take this as evidence for a *correlation between brightness and upward motion*. Consider the photograph which was taken with the slit set on the redward side of the absorption line: if we have a region which is intrinsically a little brighter than its neighbors and is also moving upward, (*i.e.* its absorption line is shifted toward the *violet*), then both for the reason that we have extra brightness—and also because the slit, being on the red side of the line, is brought more nearly into the continuum by the violet shift, we get a greater signal at that point than at the corresponding point of the other image, where the two effects work in opposite directions.

The next slide shows the Doppler field on the solar surface at larger scale, and thus reveals motions on a finer scale. Here we see motions distributed more or less randomly all over the disc, except that they die out near the limb. This represents *vertical* motion, since we see as much of it near the center of the sun as part way to the edge, and possibly *horizontal* motion also. We can't separate them as yet. The vertical motions we see near the center have no typical dimension, but the elements go right down to a size that cannot be very much larger than that of the granulation. I would call the smallest size about 3 000 km, somewhat conservatively.

Now, as I mentioned before, in taking a photograph like this the slit of the spectroheliograph sweeps from one side to the other side in a matter of some 4 or 5 minutes. If, without changing anything in the apparatus, (we only change the plate to keep from getting a double exposure) we traverse right back again in another 4 or 5 minutes, we then have at this stage two similar, possibly identical, Doppler records. However, various things can make the two photographs different; one of them is the seeing, which is never perfect. Another is imperfect guiding. However, in addition to such instrumental or atmospheric sources of difference, if there are *accelerations* which change the velocities significantly within a few minutes' time—these should show up as differences also. To bring out such accelerations we take such pairs of pictures, and then cancel out one such photograph against its mate (taking a negative of one and the positive of the other). Thus, if there were no differences at all, one should get a uniform grey field with no feature in it at all. The result is shown on the next slide. Over on one edge, corresponding to zero time difference, we see relatively little signal. What signal there is, is a result partly of the seeing and partly because in making the adjustment of one plate on the other I purposely didn't quite cancel things out at this edge, in order to attain a better average cancellation over the plate as a whole.

Near this « zero » edge, as the time difference proceeds we see the growth of a signal; the middle looks quite different than the edge. That is not entirely due to the fact that we are closer to the center of the disc, but it is a characteristic feature of all such photographs. A velocity difference builds up, exactly as we would expect. Originally, we thought to measure the lifetime of granulation this way. However, we always found that there is a second origin, farther along the image, where there is sensibly less contrast in the signal than at either earlier or later times. This is the behavior which led us to the idea of an *oscillatory motion*. It always happens that the second region of good velocity correlation corresponds to a time difference of 5 minutes between corresponding points of the two photographs.

I emphasize that the effect is not merely due to a *shift* or distortion of the image. It is an intrinsic velocity change, an acceleration, which makes a signal which goes through maxima and minima. The next slide, which brings this out in another way, represents not a Doppler *difference* such as we just looked, at, but what we call a Doppler *sum*; instead of taking two *similar* Doppler photographs, we take two which are intrinsically of *opposite Doppler polarity* and then cancel the positive one against the negative of the other—which is the same as *adding* the velocity at each point to the velocity at some time later. Zero time difference is again along one edge and we see that there is a very large signal, as we would certainly expect. However, the signal essentially *disappears* after a short time in the region near the center of the disc, and again builds up. We also see the larger cells out near the boundary of the sun which are long lived in a Doppler sum and don't ever disappear. The reduction of the signal near the center of the disc in a Doppler sum can only mean that the velocities have been reversed after a half period. We have many cases of this. It occurs very reliably, very reproducibly. We have changed the speed of traverse of the spectroheliograph and all the variables under our control, and it always shows up to one degree or another, depending upon the seeing. The average period, from 25 observations, is (296 ± 3) s. The standard deviation of a single observation is about 15 s. The next slide shows a simple Doppler field taken in the *D* line of sodium. It shows the stabilization of the motions at a high level by the magnetic fields around the sunspot group.

The next slide shows the kind of a Doppler record one gets in H_α by setting the slit rather far from the center of the line—about one ångstrom—which means that one is looking at a relatively low level in the H_α chromosphere. It can be described as consisting of large areas of essentially no Doppler velocity with « islands » of motion, little « funnels », through which the hydrogen gas is *streaming downward* into the sun. Out near the limb, of course, one sees both very dark areas and very light areas indicating horizontal motion which can be of either sign, but near the middle of the disk the predominant motion is downward through little tunnels. The tunnels shrink in size as one moves further out in the H_α line. One also sees a few little spurts here and there in which there is *upward* moving gas also.

Discussion:

— G. ELSTE:

Which line was used to show this asymmetry in the motion?

— R. B. LEIGHTON:

Principally the 6103 of Ca—both for magnetic observations and the Doppler observations.