### By R. G. GIOVANELLI\* and J. T. JEFFERIES<sup>†</sup>

#### [Manuscript received February 6, 1961]

#### Summary

A  $\frac{1}{8}$ Å birefringent filter has been used to photograph the chromosphere at various wavelengths across the H $\alpha$  line. A process of photographic subtraction has then yielded photographs of velocity distributions. At all chromospheric depths, there is a close correlation between the intensity of the granules in H $\alpha$  and the vertical velocity, the darker granules falling.

#### I. INTRODUCTION

In testing the  $\frac{1}{8}$  Å birefringent filter (Steel, Smartt, and Giovanelli 1961), we have on several occasions obtained monochromatic photographs of parts of the Sun at various wavelengths across the H $\alpha$  line. While the angular resolution is relatively poor, of the order of 5–10 sec of arc, these records enable us to study the broad features of the vertical velocity structure in the chromosphere.

The most comprehensive account of chromospheric granulation and velocities is probably that of de Jager (1957), who discussed (a) small granules (which he called "fine mottles"), diameters 4000 to 1700 km or less, seen in the core of the line, and (b) coarse granules (or "coarse mottles"), mean dimensions of the order of 45 000 km, visible mainly in the wings of H $\alpha$ . In a later discussion, de Jager (1959) distinguished between

- (i) fine mottles, diameter 10<sup>3</sup> km,
- (ii) coarse mottles, diameter  $5-8\times10^3$  km, consisting of clusters of fine mottles, and
- (iii) the chromospheric network, diameter  $5\times 10^4\,\rm km,$  composed of coarse mottles.

In the earlier paper, he pointed out that the greater contrast of the coarse granulation in the red as compared with the violet wing of H $\alpha$  is due to a correlation between line width and vertical velocity such that the coarse bright and dark regions are moving upwards and downwards respectively with r.m.s. velocities of  $\pm 1.14$  km/s. He also gave arguments for thinking of the small *dark* granules as the bases of spicules, with mean vertical velocities of  $\pm 1.8$  km/s.

Previous studies of granule velocities have usually involved precise measurements of the wavelengths of spectral lines. By contrast, the present method is based on the well-known process of photographic differencing, which makes it easier to follow the velocity distribution over extended regions of the Sun's surface and with depth in the chromosphere.

<sup>\*</sup> Division of Physics, C.S.I.R.O., University Grounds, Chippendale, N.S.W.

<sup>&</sup>lt;sup>†</sup> Division of Physics, C.S.I.R.O., University Grounds, Chippendale, N.S.W. ; present address : National Bureau of Standards, Boulder, Colorado, U.S.A.

II. PROCESS FOR YIELDING PHOTOGRAPHS OF VELOCITY DISTRIBUTIONS

Consider two photographs obtained at equal wavelength intervals  $+\Delta\lambda$ from the centre of a Fraunhofer line (H $\alpha$ ). In the absence of vertical velocities the line profile should be symmetrical and the two photographs identical. Anv vertical velocity causes a Doppler displacement of the line, the intensity increasing in one wing and decreasing in the other. Neither photograph alone is sufficient to demonstrate the presence of vertical velocities, because of the much greater intensity variations always present in the granulation; but a comparison of one photograph with another enables the Doppler displacements to be sorted out. This may be done most readily by making a unit contrast  $(\gamma = 1)$  transparent print of one of the photographs. If this is precisely superimposed on its own negative, the pair have a uniform featureless appearance in transmitted light because higher densities in the negative are exactly compensated by lower densities in the print. But, if the print is superimposed on the photograph obtained in the opposite wing, the pair show density variations where the original photographs differed, i.e. where there were different Doppler displacements on the Sun.

The original photographs were obtained on Eastman 35 mm IV E film, processed in Kodak D.19 developer for 5 min at  $20 \pm 0.5$  °C to  $\gamma \simeq 3$ . For convenience, these have been enlarged  $2 \times$  on Ilford N.30 plates, with brush development in one part of Ilford ID2 to four parts of water for 4 min at  $20 \pm 0.5$  °C, yielding  $\gamma \simeq 2$ . The unit gamma prints are obtained by brush development of Ilford N.30 plates in Kodak D.76 at  $20 \pm 0.05$  °C;  $\frac{1}{4}$  gallon of developer is used per plate, the time being very closely controlled and lying in the range 5 min 35 s to 6 min 10 s, depending on the batch of developer. Prints of the superimposed plates are usually made on Ilford N.30 plates processed to  $\gamma \simeq 2$ .

While we believe that Doppler displacements are the predominant physical cause of asymmetric  $H\alpha$  profiles, the final photographs showing the apparent velocity distributions may suffer from various defects of instrumental or processing origin. For example, the central wavelength transmitted by the filter varies by about 0.01 Å across its surface, resulting in an apparent velocity variation across the final picture; though this is constant from picture to picture, and can be easily recognized or cancelled out if necessary. Again, it is difficult to make prints of precisely unit contrast; the control is such that usually  $\gamma=1\pm0.02$ . Whether or not these limits are adequate depends on the intensity variations due to velocities as compared with normal variations across the granules; if necessary, a technique is available for a further stage of cancellation with an effective overall  $\gamma$  negligibly different from unity, though at the cost of additional photographic "noise". The various checks used leave us confident that the final photographs represent chromospheric velocity distributions.

Plate 1 shows the chromosphere near the centre of the disk on August 11, 1960, the filter transmission maxima being respectively 0.2, 0.5, and 0.7 Å from the centre of H $\alpha$  on the successive rows of photographs. In each case, the left-hand picture shows the intensity distribution in the red wing, the right-hand

#### **R. G. GIOVANELLI AND J. T. JEFFERIES**

picture shows the velocity distribution. Plate 2 shows corresponding intensity distributions at the line centre (a) and in the continuum (b). Plate 2 (c, d) shows intensity and velocity distributions at  $\Delta \lambda = 0.5$  Å on June 10, 1960. A careful comparison of the intensity and velocity distributions reveals a very close correlation, as found by de Jager for the coarse granulation, except that it now appears to hold for fine granulation also; the bright granules are almost invariably moving upwards, the dark ones downwards.

# III. INTENSITY AND VELOCITY STRUCTURES IN THE CHROMOSPHERE

Apart from sunspots, whose velocities are shown incorrectly owing to the limited photometric range of the photographic emulsions, we may note filaments, general chromospheric granulation, and active (plage) regions on these plates. The main present significance of the filaments is in checking the photographic method of revealing velocities. For example, there is a filament on the left-hand side of Plate 2 (c), just above a small spot group. The velocity picture, 2 (d), shows that the right-hand end of the filament is rising, the left-hand end falling.

In considering the granulation, it is important to bear in mind the limited angular resolution, perhaps 5 sec of arc at best, despite which interesting comparisons can be made with de Jager's findings.

## (a) General Chromospheric Granulation

Plates 1 (a, c, e) and 2 (a) clearly show the well-known differences in chromospheric structure at different wavelength settings. Though described often enough previously, it is important to reconsider them now that velocity distributions are available for comparison. In particular, it is to be remembered that the various features seen at the one wavelength arise from a more-or-less similar optical depth, but may differ radically in height above the photosphere. With this reservation, we can distinguish at least two major chromospheric levels :

- (A) There is little change in the appearance of the granules from the line centre out to  $\Delta \lambda = \pm 0.2$  or even  $\pm 0.3$  Å. Near active regions, the granules are drawn out to lengths of several minutes of arc, but they are all narrow; elsewhere they are more compact.
- (B) By  $\Delta \lambda = \pm 0.4$  Å, and more particularly  $\Delta \lambda = \pm 0.5$  Å, and out to say  $\Delta \lambda = \pm 0.7$  Å, the structure is on the whole much coarser and more contrasty, with broader bright regions separated by narrower dark channels; these both have fine structures, the dark channels being subdivided into sequences of dark points and the bright regions crossed by faint dark markings. By  $\Delta \lambda = \pm 0.7$  Å, the granulation is somewhat simpler, the structure having almost disappeared in the bright regions. By  $\Delta \lambda = \pm 1.0$  Å, the dark points and channels are only just discernible.

There is little difficulty in identifying the coarse structure of level (B) with de Jager's coarse granulation or chromospheric network. In the core of the line  $(\Delta\lambda \leqslant 0.2 \text{ Å})$  our resolution is inadequate to show de Jager's very fine granulation properly; what we see corresponds almost certainly to what he described in 1959 as "coarse mottles", consisting of clusters of very fine granules.

214

The features at levels (A) and (B) are by no means independent. Most of the dark points in the lower level (B) can be identified as dark points in the upper level (A) where, however, they are otherwise indistinguishable from other fine dark granules. Similarly, the faint structures in the bright granules of (B) coincide with granules in (A). We can find no evidence for de Jager's (1957) comment: "The coarse mottling" (i.e. granulation) "remains faintly visible even in the very centre of the line. It seems further that the coarse structure at  $\Delta\lambda=0.0$  Å is more or less a negative image of the coarse structure at  $\Delta\lambda=0.4$  Å. Bright patches in the line centre seem to be dark at 0.4 Å and vice-versa."

The velocity is closely correlated with intensity in both (A) and (B). At  $\Delta\lambda=0.7$  Å, the predominant features of the velocity pattern are a set of downward moving "points" (i.e. dark in Plate 1 (f)) which coincide with the dark points of Plate 1 (e). There is also a smaller number of upward moving "points" in Plate 1 (f); these occur in the broad, bright granules, but there seems to be very little on the intensity picture to distinguish them.

At  $\Delta\lambda=0.5$  Å, there is more detail than at  $\Delta\lambda=0.7$  Å, but the velocity distributions are still very similar. Almost every downward or upward moving point at  $\Delta\lambda=0.7$  Å lies immediately below a similar point at  $\Delta\lambda=0.5$  Å, but at the higher level a velocity structure is now obvious between the points, while the upward moving points are more pronounced. The correlation between the intensity and velocity patterns at  $\Delta\lambda=0.5$  Å is very strong.

As with the intensities, the differences between the velocity distributions at levels (A) and (B) are very considerable. Nevertheless, some connexion can be found. Most of the falling and rising points at  $\Delta\lambda=0.5$  Å can be detected as similar points at  $\Delta\lambda=0.2$  Å, though at the higher level the relative velocity variations differ considerably from those lower down. As before, there is a very close correlation between the intensity and velocity distributions at  $\Delta\lambda=0.2$  Å, the dark granules descending and the bright granules rising. In particular, the long-drawn-out granules near active regions appear to be rising or falling uniformly along their lengths.

### (b) Active Regions

The plage regions are very different in their vertical structure. At the centre of H $\alpha$  the most obvious features are the bright cord-like flocculi. These are very faint at  $\Delta\lambda=0.4$  Å, and have almost disappeared by  $\Delta\lambda=0.5$  Å. At the latter wavelength a broad dark region underlies and extends beyond the bright flocculi, which are still marked by a faint brightening. The dark region possesses a fine structure rather like that of the granulation in quiet regions, though darker; it appears to be almost identical with that of the overlying granulation seen in the core of the line where not obscured by bright flocculi, and persists quite clearly to  $\Delta\lambda=0.7$  Å. At  $\Delta\lambda=0.5$  Å, the well-known drawnout structure of the granules near plages commences immediately beyond the dark region. The latter has disappeared by  $\Delta\lambda=1.0$  Å, where the plages appear bright once more, though much less obvious than at the line centre.

As before, the velocity and intensity distributions are closely related. The broad, dark region at  $\Delta\lambda = 0.5$  Å is probably slowly sinking as a whole, though

within it there is the familiar pattern of rising and falling granules. At  $\Delta\lambda=0.2$  Å, the velocity pattern is much less pronounced than elsewhere on the Sun. It has not been established as yet whether there are vertical motions in the bright flocculi.

### IV. DISCUSSION

The most striking aspect of these results is the almost universal association between granule intensity and velocity. However, any temptation to attribute this to buoyancy effects must be resisted, at least for the time being, because the intensity in  $H\alpha$  is far from a simple function of gas temperature. It will be an important future task to unravel the origin of the correlation.

The extraordinary general velocity pattern appears to be somewhat as shown schematically in Figure 1, with narrow columns rising or falling through



Fig. 1.—Schematic diagram of normal chromospheric velocity structure. Chromospheric heights are represented by the distance from the centre of  $H\alpha$  at which the features may be seen.

the chromosphere.\* These columns often occur in widely spaced arrays which, in the lower chromosphere, are separated by relatively undisturbed regions. In the higher chromosphere, the velocity pattern has a much finer structure.

It will be of considerable interest, when higher angular resolution is available, to see whether the intensity-velocity correlation found here applies for the fine, dark granules observed by de Jager in the H $\alpha$  core, and considered by him to represent the bases of spicules. Their height-time curves suggest that spicules rise to their maximum heights, after which they may fade or may descend back to the chromosphere, the upward and downward velocities being similar in magnitude. Rush and Roberts (1954) have pointed out that apparent *downward* velocities may be due to variations in excitation rather than actual downward motions. But if the very fine dark chromospheric granules all turn out to have downward motions, this will necessitate a reinterpretation of their relationship to spicules.

\* In a personal communication, Dr. R. B. Leighton also has reported a distinct columnar structure in the Doppler field in the lower chromosphere.







Solar chromosphere near centre of disk, August 11, 1960. The left-hand pictures (a), (c), and (e) are normal photographs obtained in the red wing of H $\alpha$ . The right-hand pictures (b), (d), and (f) show the corresponding velocity distributions (see Section II); rising and descending regions appear bright and dark respectively, except in sunspots, where velocities are distorted. A dark vertical band on the right-hand side of (b) is spurious, being due to a slight wavelength variation across the filter.

Aust. J. Phys., Vol. 14, No. 2





 $\varDelta \ \lambda = o \cdot o \ \mathring{A}$ 



 $\Delta \lambda = 5$  Å



(a) and (b) are normal photographs of the region shown in Plate 1, obtained in the H $\alpha$  line centre and in the continuum. (c) shows, on a smaller scale, a normal photograph 0.5 Å from the centre of H $\alpha$  on June 10, 1960, (d) being the corresponding velocity distribution. The curved arc near the upper left-hand corner is due to a diaphragm; the upper right-hand corner is close to the Sun's limb.

Aust. J. Phys., Vol. 14, No. 2



## V. ACKNOWLEDGMENTS

It is a pleasure to acknowledge the assistance of Miss M. K. McCabe and Mr. H. R. Gillett, who have developed the reproducible methods of controlling photographic processes required for this work.

# VI. References

DE JAGER, C. (1957).-Bull. Astr. Insts. Netherlds. 13: 133.

DE JAGER, C. (1959).—" Paris Symposium on Radio Astronomy." p. 89. (Stanford Univ. Press.)

RUSH, J. H., and ROBERTS, W. O. (1954).-Aust. J. Phys. 7: 230.

STEEL, W. H., SMARTT, R. N., and GIOVANELLI, R. G. (1961).-Aust. J. Phys. 14: 201.