PAPER 56

CONCLUDING LECTURE by

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During this part of the Symposium, so carefully prepared by Messrs. Denisse and Pawsey, a great amount of new data has been presented, almost all obtained since the last international meeting on these subjects only one year ago. It is clear that this is a part of astronomy that develops impetuously. Hypothetical theories have been definitely confirmed by direct observation; on the other hand, new facts have been disclosed, increasing the complication of the phenomena; but we have reason to hope that we are in a transitory stage and that the complications will gradually be explained on clear and simple principles. It is of course impossible to mention in this summary the contents of all communications; only the more essential results will be reviewed.

Considering first the new instrumental developments, we realize that the great progress is due to big *interferometers*, which for the first time define the details on the solar surface; this is especially true for the *pencil-beam* instruments. Next to these, we have the *radiospectrographs*, which convey a more intimate knowledge about what happens in the solar envelopes. Finally *polarization*, which plays only an accessory role in optical astronomy, gives important information to the radio astronomers, since the existence of polarization always reveals the presence of a magnetic field.

The aim of all radio-astronomical observations of the sun is to derive a model of the solar envelope with its perturbations. The excellent summary in tabular form, prepared by Dr. Denisse (paper 14) is the best guide through this whole field.

1. THE RADIATION OF THE QUIET SUN

The radio radiation of the quiet sun is directly connected with the model of the outer solar envelope.

If first we want to understand from general principles why a chromosphere and a corona are formed, we find a satisfactory explanation in the considerations of Dr. de Jager on the energy balance in these layers: turbulent motions ascend above the photosphere, up to such a height that the inflow of mechanical energy is compensated by the outflow of radiation and by the downward thermal conduction. The steep temperature increase above 4000 km then becomes understandable.

Looking now into details of the models proposed, we see that they are becoming more and more refined. (*a*) Most modern models picture the chromosphere as inhomogeneous, the solar surface exhibiting much mottling (in the

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lower layers) and spicules (in the higher regions); whether these spicules are hotter or colder than the surroundings is still a matter for discussion. This "pincushion" is what Athay and Thomas (16) call a "non-spherically-symmetric model"; with it Athay is able to explain the properties of the radio radiation between 0.4 cm and 21 cm. (*b*) In another sense we may say that a deviation from spherical symmetry has to be introduced, because the corona appears to have different structures at the poles and at the equator. This deviation is found moreover from optical as well as from radio data. For the optical minimum corona van de Hulst had already tabulated separately the electron density above the poles and above the equator. Newkirk (25), by using the coronograph observations, finds similar differences even for the maximum corona, and de Jager (15) presents an interesting collection of curves derived from many sources, giving the distribution of the radio radiation along the polar and the equatorial diameters and all showing the same asymmetry. (*c*) From a comparison between the minimum and the maximum coronas, it was already clear that the model varies according to the phase of the 11-year cycle. This periodicity is also very apparent in the classical measurements of Covington (28) at 10 cm, which extend now over a complete solar cycle (1947-58). Others have found variations from month to month or from day to day (Boischot at 1.70 m, Firor at 0.88 m), even when local active centers are entirely lacking.

2. THE SLOWLY VARYING COMPONENT (FIG. 1)

The *plage* is the typical disturbed solar area. Its size may be of the order of 250,000 km, corresponding to 5 minutes of arc. Probably a magnetic field extends over this whole area, influencing strongly the low chromospheric layers and having lesser and lesser effects the higher we ascend.

The lowest layer above the plage has been studied at 3 cm by Gutmann and Steinberg (21), Kundu (43), and Vitkevich and his associates (23). There are local centers, not greater than 2 minutes of arc, where circular polarization appears, doubtless because the magnetic field reaches up to this layer. The contour of the emitting region corresponds with that of the plage.

Christiansen and Mathewson (19) study on 20 cm a slightly higher layer (40,000 km). With their high resolving power they are able to inform us definitely about the contour of the emitting layer, which again is found to coincide with that of the plage. The corona there is denser than in a normal region, but it has the normal temperature. No polarization is found; apparently we are already too far above the field region.

Somewhat higher again extends the layer where Waldmeier (20) studies the green corona line. The relation between the shape of the coronal condensations and the plage is less close, though a general correspondence still exists. On 50 cm the area of the disturbed region has increased (Vauquois, 26); at wavelengths of 88 cm (Firor, 18) and 177 cm (Boischot, 33), corresponding to still greater heights, it gradually takes the character of an *R center*, of which the connection with the plage becomes much looser and which may be considerably displaced, its position changing from day to day.

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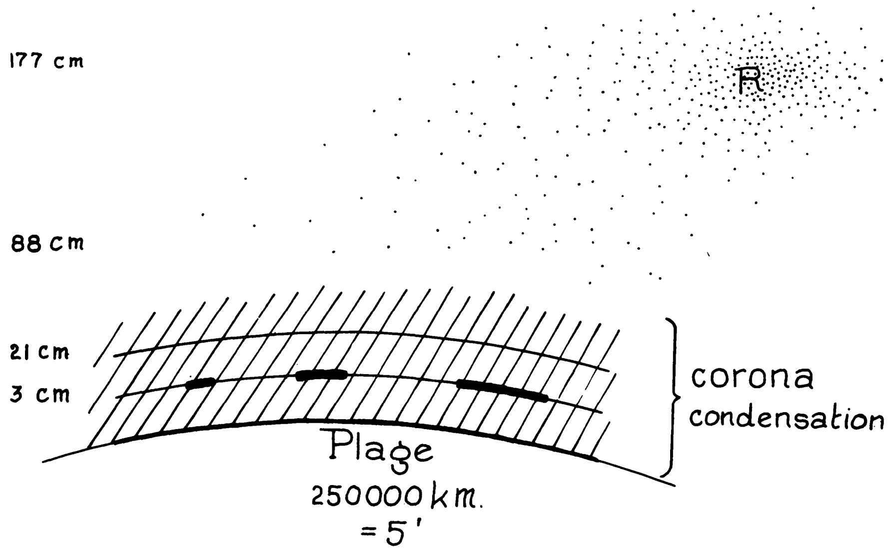

FIG. 1. Disturbed region above plage, origin of enhanced radio radiation.

At 88 cm we observe sometimes slowly varying radiation, and at other moments storm bursts from the same active center; at 177 cm we observe only bursts. The temperature of the *R* center is estimated to be between 10^6 and 10^7 °K.

Thus we get a general picture of the whole coronal condensation above the plage, studying it, so to say, by sections at successive heights. It will be necessary to investigate also the influences which these different layers exercise on each other and which keep the disturbance together.

3. THE RADIO BURSTS (FIG. 2)

The great variety of phenomena described as radio bursts is rapidly increasing and it is only with the help of spectral records that a better understanding and classification of these emissions becomes possible. For the moment it seems that we have to distinguish mainly between ***monochromatic emission***, which might be explained as a plasma oscillation, and ***continuum emission***, which is often interpreted as synchrotron radiation, though we should remain aware that other explanations, for example the Čerenkov effect, are equally possible.

From the classical radio spectra of the Australians it was well known that three main types of bursts should be distinguished (pp. 86–87). For type I the wavelength remains constant during the existence of the burst. For type II the wavelength increases slowly, for type III it increases quickly.*

On the *bursts of type I* several studies at meter wavelengths have been

* It would be useful if everybody would plot these spectra according to a standard convention, e.g. take time as the abscissa, and wavelength as the ordinate.

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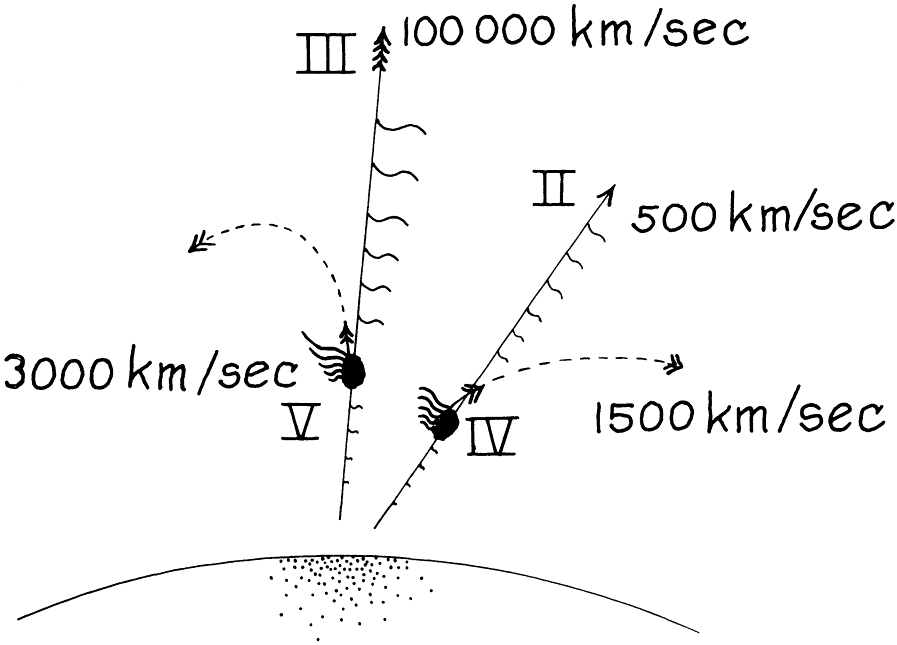

FIG. 2. Emission of radio bursts of types II, III, IV, V. The emitted wavelengths are indicated by short sine waves.

reported during the symposium. The centers that produce them have a size of 1 to 9 minutes of arc and are located in part of the *R* regions (Simon *et al.*, 45); during a noise storm the positions of the individual bursts remain remarkably constant within 3 minutes of arc (Högbom, 48). Their detailed profile in frequency and time has been studied by de Groot and Elgarøy with high-speed recorders. These are probably the shortest of all known solar phenomena, their duration being only 0.1-0.2 seconds. Very curious is the polarization, which is constant for a few days and then changes rather suddenly (Alekseev and Vitkevich, 50). At 1.50 m this polarization does not show any correlation with the polarity of the neighboring spot, apparently because the level is much too high (Cohen and Fokker, 49). At much shorter wavelengths of 3 to 30 cm, the polarization is stronger and the correlation is evident (Tanaka and Kakinuma, 41).

For the bursts of type II and III we now have for the first time direct confirmation that they are produced by rapidly ascending disturbances, which along their path excite electromagnetic oscillations in the successive layers of the corona. This important progress we owe to the work of Wild, Sheridan and Trent (32), who used a swept-frequency interferometer giving the position with a precision of 1 minute of arc. The velocities of ascent may be calculated now (1) from the frequency drift, the appearance of each frequency meaning that the disturbance reached the height where this plasma oscillation originates; and (2) from the interferometer positions, giving directly the transverse velocities, except for a projection factor.

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The velocities found by these two methods are of the same order, but those derived by the second method are, in general, greater. Apparently this may be explained by assuming that the conditions in the corona above the disturbed area are not adequately described by the ordinary models. If the density in this region is higher than normal, the velocity of ascent, calculated from the frequency drift, will be found greater and the agreement with method (2) is improved. The velocities directly obtained from transverse motions reach 10^5 km/second in the case of type III bursts and 500 km/second in the few observed cases of type II bursts; the first value is already near the velocity of cosmic rays, the second one is near to the geophysical values.

(3) Actually there has been given a third independent method of measuring: the observations of ascending prominences made by Giovanelli. It is most gratifying to find here again velocities of ascent of quite the same order as for type III.

Type II bursts often show fine structures, frequency splitting, herringbone structure. In 60 per cent of the cases, a fundamental and a second harmonic band have been observed, often of the same order of intensity, while the third harmonic was invisible. The work of Roberts and Thompson shows that these are the bursts that produce magnetic storms on earth; Roberts (35) finds a delay of 1 to 3 days, Thompson (39) distinguishes a maximum after 1 to 2 days and another one after 4 to 5 days.

Type III bursts are always associated with flares, often small flares, and more especially with those showing sudden puffs or dark markings that move away from the flare. According to Cohen and Fokker (49) the polarization they present on 1.50 m is weak and irregular. Hitotuenagi finds, to the contrary, 50 per cent of strong polarization; this difference may be due to the wavelengths used: in the first case we are concerned with longer waves, thus with higher layers, where the magnetic fields are not directly connected to the spot below.

Next to the three "classical" types of bursts, new types IV and V have been studied by Boischot (33), Gutmann, Haddock and Maxwell, Wild and his associates (32). *Type IV* is an emission of continuous radiation, with a low frequency cut-off, mostly following a strong flare with a type II burst. It develops smoothly, reaches a maximum after 20 to 40 minutes and may last from 1 to 3 hours. The emitting center appears to have a size of the order of 10 minutes of arc; often it moves upward with a speed varying between 500 and 5000 km/second and then stabilizes; it has an equivalent temperature of 10^{10} to 10^{12} °K. Most interesting is a possible connection with the cosmic rays (Denisse, 44), which up to now we had thought to be related to the type III bursts.

Type V is also a continuum emission extending over a very broad band, but here the centimeter wavelengths are particularly enhanced. It is much shorter and stronger than type IV. It generally follows a type III burst and ascends with a speed of the order of 3000 km/second.

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Another group of bursts, the *U bursts*, have been investigated by Haddock (34) who found different regularities in these phenomena.

As to the *bursts on centimeter waves*, they have to be treated provisionally as a separate category, since no spectra are available. More information on this subject is badly needed! It is interesting to compare the classification as given by Kundu and Denisse (43 and 44) with that of Covington (28). Polarization is rather general but complicated; here again the connection with the spot and the hemisphere on which the disturbance occurs is much greater at small wavelengths (Tanaka, Kundu, 41 and 43).

Finally there is the *November* 4 *event* (51), characterized by a high intensity on meter waves and a very special type of fluctuations. This certainly shows that many surprises are still awaiting us if we observe carefully and continuously.

One of the most important open questions concerns the nature of the ascending source which produces the bursts of types II, III, IV, and V: shock waves, magnetohydrodynamical waves, or corpuscles?

4. STRUCTURE OF THE OUTER CORONA (FIG. 3)

Some years ago, Vitkevich suggested a new method for investigating the corona: the Taurus radio source is occulted every year by the outer parts of the corona, and precious information may be obtained by observing the radio source during this passage. Effects are observed even at distances up to 20 solar radii. (*a*) The apparent diameter of the source increases near the

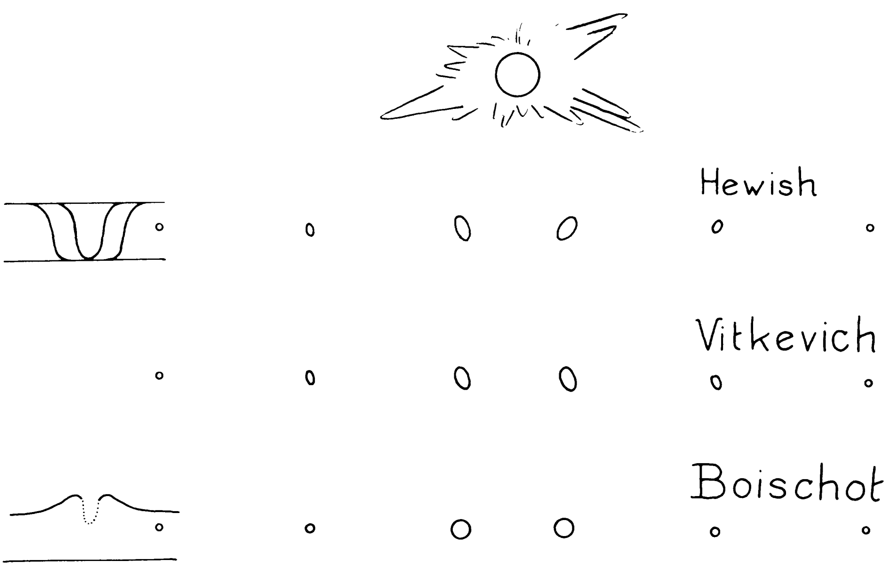

FIG. 3. Occultation of the Taurus source by the outer corona. Apparent size and shape of the radio source.

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sun; (*b*) its shape becomes elliptical; (*c*) the radiation flux changes; (*d*) in general the position is not perceptibly shifted (<30 seconds of arc); (*e*) no marked circular polarization is observed.

The results of different observers are summarized in Fig. 3. Especially regular and clear are the Cambridge results, with which the Russian measurements are in general agreement. The French results, however, show a remarkable radiation increase near the moment of closest approach, which is difficult to understand, considering that no change in the apparent position of the source is observed.

Most of these effects may be explained by inhomogeneities, directed along the lines of force. There is a regular bending of the radio-beam ("refraction") and an irregular refraction in all directions, but especially perpendicular to the inhomogeneities; this means perpendicular to the magnetic field ("scattering").

When the results of different years are compared, typical differences appear that are dependent on the phase of the solar cycle, suggesting that even at these great distances from the sun the corona shows similar variations in form as the nearer visible corona does.

By such observations, data are obtained on the irregularities in the corona, which seem to have a size of 10^4 to 10^6 km and on the magnetic field, which is not a true dipole field but appears to be more nearly radial.

In this brief summary we have been obliged to mention only some of the most striking results, among the great quantity of interesting new data. One might perhaps ask whether this radio astronomy of the sun is sufficiently connected to the radio astronomy of the galaxies, to be discussed in the same symposium. The connection is to be found in the question: *how does the emission of the cosmic radio-radiation take place?* The organizing committee has wisely postponed the discussion on this fundamental problem to the last session, which, we hope, will turn out to be the climax of this colloquium.

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