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HISTORICAL INTRODUCTION

1.1 Early visual observations of the photospheric granulation

No serious attempt to elucidate the fine structure of the solar surface was made until the beginning of the nineteenth century, when the problem attracted the attention of the famous English astronomer Sir William Herschel (1738–1822). Observing the Sun with a reflector of focal length about 3 m fitted with a speculum mirror of his own manufacture, Herschel interpreted what he saw in the light of his own highly exotic views regarding the habitability of the Sun. 'On a former occasion', he wrote in 1801, 'I have shewn that we have great reason to look upon the Sun as a most magnificent habitable globe'. Herschel pictured the solar disk as being covered by *corrugations* which, he said, 'I call that very particular and remarkable unevenness, ruggedness, or asperity, which is peculiar to the luminous solar clouds, and extends all over the surface of the globe of the Sun. As the depressed parts of the corrugations are less luminous than the elevated ones, the disk of the Sun has an appearance which may be called mottled'. From this description it seems clear that Herschel did not resolve the individual photospheric granules as such but rather the large-scale pattern of brightness fluctuations which appears when the granulation is viewed with inadequate resolving power or under mediocre conditions of atmospheric seeing.

After Herschel, interest in the problem of the fine structure of the solar disk languished until, in the early 1860s, it suddenly became the centre of a spirited controversy involving many of the foremost solar observers of the day. The originator of the controversy was the English engineer James Nasmyth (1808–90), who is remembered as the inventor of the steam hammer and as an assiduous observer of the Moon. At his factory at Bridgewater, near Manchester, Nasmyth had all the facilities for casting and polishing specula. With his largest mirror, a 50-cm, he constructed a Cassegrain–Newtonian telescope on an alt-azimuth mounting. After his retirement to Penshurst in Kent, Nasmyth used this telescope to make many observations of sunspots and the solar photosphere, using a high-powered eyepiece and choosing moments when the seeing was best.

These observations led him to announce in 1862 that the Sun's surface was actually covered by a compact pattern of thin bright filaments shaped much like 'willow-leaves'. According to Nasmyth, the 'willow-leaves' were extremely regular in shape and size but crossed one another in all possible directions, the dark interstices between them giving rise to the mottled appearance of the disk. Nasmyth's conception of the willow-leaf pattern is illustrated in Fig. 1.1, which is a reproduction of a drawing that he made on 5 June 1864 of a sunspot group and the surrounding photosphere.

Nasmyth's announcement of his discovery of the willow-leaf pattern sparked off a number of searching discussions throughout the astronomical world. One experienced English observer, the Reverend William Dawes (1799–1868), flatly denied the existence of such structures; he stoutly maintained the view (which he considered well established) that the mottling of the solar surface shows every variety of irregular form except in the immediate vicinity of sunspots. The observers at the Royal Greenwich Observatory claimed to corroborate Nasmyth, although their description of the pattern in terms of interlaced *rice grains* represented a retreat from Nasmyth's extreme view of the regularity of the basic structure. The First Assistant, E. J. Stone, made grain counts with an altazimuth transit instrument of 9.5-cm aperture that yielded a rough dimension of between 1″.5 and 2″ of arc.

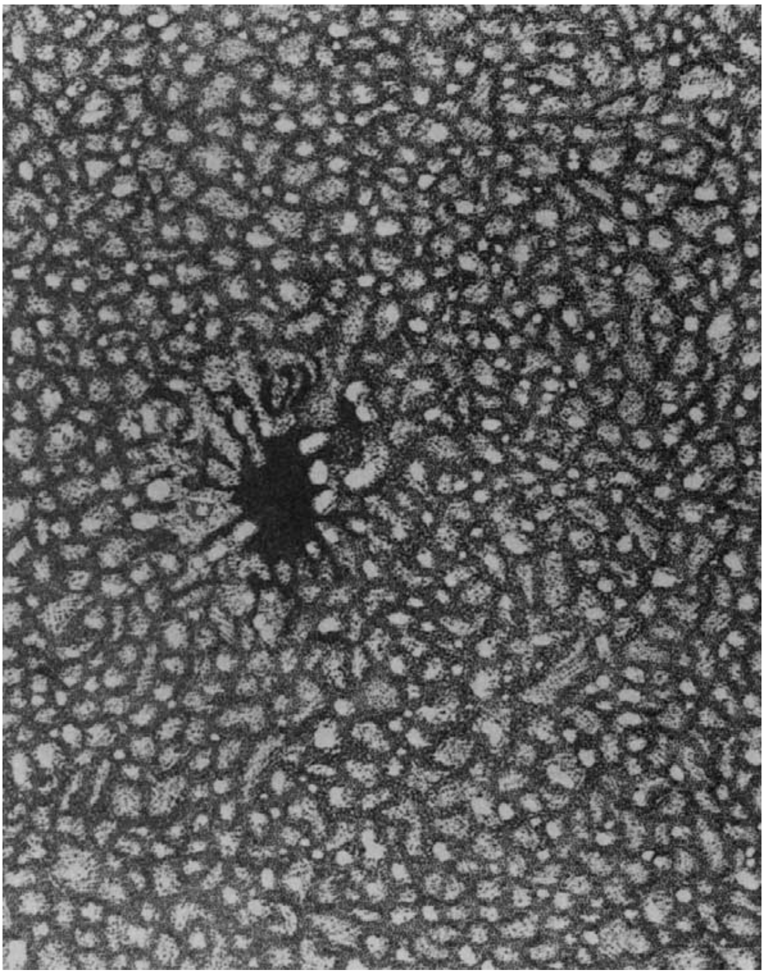
The famous Italian astronomer Father Secchi (1818–78) derived from his own observations a picture of the photospheric fine structure which was much closer to reality. He described the solar surface as being covered by a multitude of small bright features, which he also likened to grains, separated by lanes of darker material. The grains were similar in size but differed considerably in shape. Fig. 1.2 is a reproduction of one of Secchi's own drawings taken from his treatise *Le Soleil*, showing the pattern in the neighbourhood of a small sunspot pore.

While the morphological details of Secchi's drawing constitute a fair approximation to the truth, the same cannot be said of his attempt to measure the sizes of the individual grains. He derived a figure of about 0″.3, whereas modern observations yield a representative value for the diameter of the granules of 1″.3 (Section 2.3.2). Similar measurements were made by another assiduous visual observer, S. P. Langley (1834–1906), who in 1867 was appointed director of the Allegheny Observatory in the USA and later became secretary of the Smithsonian Institution and a notable pioneer in the new science of aerodynamics. Using the 33-cm Allegheny refractor, he found that the average diameter of the grains was between 1″ and 2″ but claimed that, at the moments of best seeing, the individual grains appeared as conglomerates of smaller elements not exceeding 0″.3 or 0″.4 in width.

Fig. 1.1. Drawing of a large sunspot group and the surrounding photosphere made by James Nasmyth on 5 June 1864, illustrating his conception of the appearance of the solar disk as a concentrated pattern of thin bright filaments or 'willow-leaves'. According to Nasmyth, the 'willow-leaves' were extremely regular in shape and size but crossed one another in all possible directions, the dark interstices between them giving rise to the mottled appearance of the disk.

The visual observer whose description of the photospheric fine structure came closest to the truth was the English astronomer Sir William Huggins (1824–1910), who is remembered primarily for his important contributions to the field of stellar spectroscopy. According to Huggins the grains, which he preferred to call

Fig. 1.2. Drawing of the photosphere in the neighbourhood of a sunspot pore published by Father Secchi in his book *Le Soleil* (1875). He pictured the solar surface as covered with a multitude of small bright features ('grains') separated by lanes of darker material. Secchi's grain structure bears a fair resemblance to the photospheric granulation pattern although, unfortunately, no scale was given on the original drawing.



by the name *granules* suggested by Dawes in 1864, were distributed over the entire solar surface and were more or less round or oval in shape, although more irregular forms did occur. Their diameter he estimated to lie between 1″ and 1″.5, in agreement with the modern figure. Huggins' note published in 1866 in the *Monthly Notices of the Royal Astronomical Society* effectively terminated the controversy over Nasmyth's 'willow-leaves'. Unfortunately, however, Huggins went beyond his realistic description of the individual granules to claim that they were grouped to form a variety of fantastic shapes and patterns; these he illustrated by a drawing, which the interested reader will find reproduced in Young's book, *The Sun*.

1.2 Pioneering photographic observations of Janssen, Hansky, and Chevalier

On 13 August 1877 the French astronomer Pierre Jules Janssen (1824–1907) rose before a meeting of the Academy of Sciences in Paris and announced that he had successfully photographed the photospheric granulation. Born the son of an eminent musician and educated at the University of Paris, Janssen achieved fame by the discovery in 1868 – made independently and nearly simultaneously by Sir Norman Lockyer – that with the aid of a spectroscope it was possible to see prominences outside of an eclipse. As a result of this work he was appointed director of a new astrophysical observatory set up at Meudon, in the vicinity of Paris (Fig. 1.3). There, using a refractor of 13.5-cm aperture, he quickly brought the art of high-resolution solar photography to a high degree of perfection. In fact, when the American astronomer Langley visited Meudon in 1877, he remarked that during his many years of visual observations there had been only five or six occasions when he had seen photospheric detail with a clarity equal to that of Janssen's photographs – and then only for a few seconds at a time.

Fig. 1.4 is a reproduction of part of a photograph obtained by Janssen on 1 April 1894. It shows clearly that the photospheric granulation in the central region of the solar disk consists of a well-defined pattern of bright granules with diameters lying mostly in the range 1–2″, separated by lanes of darker material. The resolution is, in fact, comparable to that of modern granulation photographs taken with telescopes of similar aperture. A number of factors contributed to Janssen's success: the choice of a telescope of a type suitable for high-resolution solar photography; the use of an enlarging lens to obtain a large effective image diameter (30 cm) with a relatively short optical path; and the employment of a 'flying-slit' shutter to achieve very short exposure times. Yet despite these notable advances in technique, Janssen's observations contributed very little to our knowledge of the properties of the individual photospheric granules, principally because he was side-tracked into devoting most of his effort to studying a large-scale pattern of distortions occurring on many of his photographs, to which he gave the name *réseau photosphérique*. Janssen believed this pattern to be an actual feature of the solar surface, produced by violent movements of the granules in certain localized areas. However, the work of many subsequent observers has conclusively shown that the *réseaux* are due entirely to the effects of poor atmospheric seeing.

Fig. 1.3. Pierre Jules Janssen, the famous French astronomer, who was the first to photograph successfully the photospheric granulation. His statue stands in the grounds of the Meudon Observatory, with the city of Paris in the background.

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Excerpt
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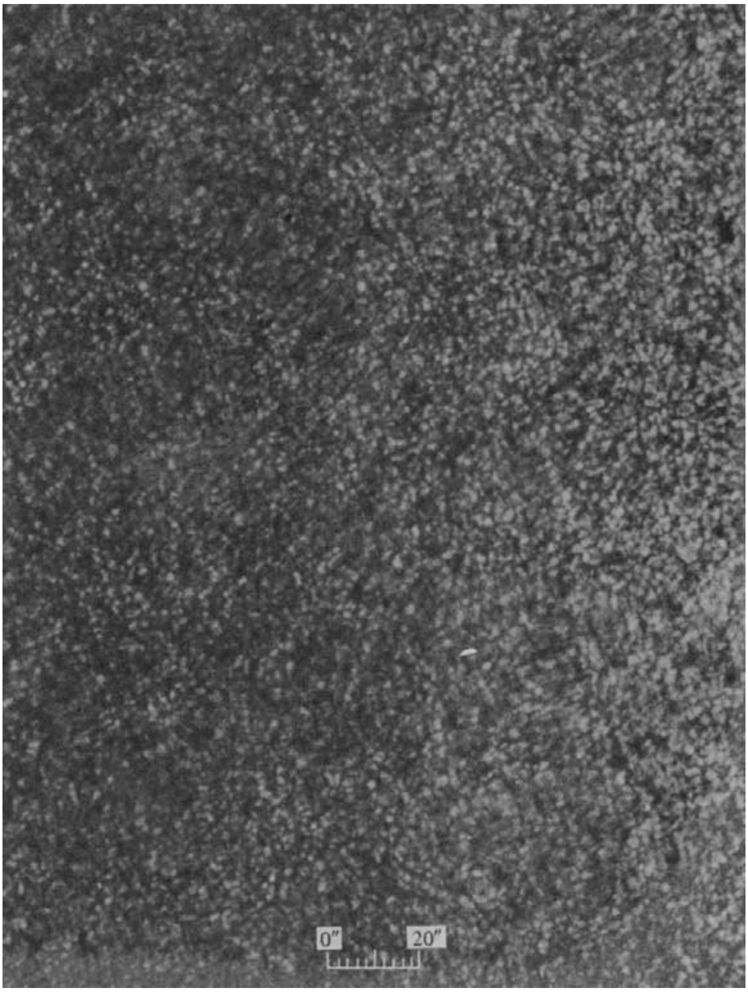
In all, Janssen's photospheric observations extended over a period of some twenty years. They were published in collected form in 1896 in a volume which also contains reproductions of twelve of his original photographs. Plate X of this collection is well known: it is the one on which the granulation appears to show a striking resemblance to a very regular polygonal convection pattern. (Part of

Fig. 1.4. Reproduction of part of a photograph of the photospheric granulation obtained by Janssen on 1 April 1894. Although marred by seeing, it shows clearly that the granulation consists of a well-defined pattern of bright granules mostly 1–2″ of arc in diameter, separated by lanes of darker material.



this photograph has been reproduced by Kiepenheuer, 1953: see Fig. 13.) However, in the light of modern knowledge, we must regard this particular photograph with a good deal of suspicion. In the first place, the granulation pattern appears to be *too* regular, whereas we now know that there is actually a considerable diversity in the sizes and shapes of the individual granules (cf. Figs. 2.1 and 2.2). Secondly, a careful examination of Janssen's original reproduction shows that in the regions of the photograph where the regular polygonal appearance is most marked, the individual features have diameters lying mostly in the range 2–4″, according to the scale given by Janssen. These features are therefore about twice the size of normal photospheric granules and we must consequently attribute their origin to some spurious effect. One possible explanation may lie in the action of surface tension forces during the processing of the original plate, which was of the wet collodion type. Drying paint films, for example, often display regular, convection-like patterns produced by variations in surface tension (see Section 3.4.1).

The first observer to point out the atmospheric origin of Janssen's *réseau photosphérique* was the young Russian astronomer Alexis Hansky (1870–1908). Educated at the University of Odessa, he spent some time at the Meudon Observatory before returning home to Russia where, in 1905, he was appointed an assistant astronomer at the Pulkovo Observatory near Leningrad. There, using a conventional astrograph and an enlarging camera, he turned his attention to high-resolution photography of the solar disk. His main interest lay in the photospheric granulation, and he succeeded in obtaining granulation photographs showing somewhat better resolution than those of Janssen himself. Moreover, Hansky deserves special credit for realizing the importance of obtaining sequences of granulation photographs taken at short time intervals apart in order to study changes in the granules with time. Although his attempts to obtain sequences were only partially successful, Hansky nevertheless derived an estimate of about 5 min for the mean lifetime of the photospheric granules – about one-third of the correct value (cf. Section 2.3.6). On the other hand, he erroneously concluded that the granules execute horizontal oscillations about a mean position with speeds of up to 4 km s^{-1}, failing to appreciate that their apparent lateral displacements from photograph to photograph were due – like Janssen's *réseaux* – entirely to the effects of atmospheric seeing (see Section 2.2.1).

In 1908 Hansky went to the Crimea, where the Pulkovo Observatory had recently established a southern station, with the intention of continuing his observations of the granulation under more favourable climatic conditions. However, just as his programme was about to start, he tragically lost his life while bathing in the Black Sea.

A third pioneer in the art of high-resolution solar photography was Father Stanislas Chevalier (1852–1930), for many years the director of the Zô-Sè

Observatory in China. This observatory was founded as a branch of an older Jesuit observatory situated at Zi-Ka-Wei on the outskirts of Shanghai. The Zô-Sè Observatory was built on a low hill some 24 km from Shanghai and was equipped with twin 40-cm refractors of 7-m focal length carried on the same equatorial mounting, one designed for visual work and the other for photography. Although the instrument was brought into operation in 1901, observations of the Sun did not start until 1904. Chevalier's photographs, like those of Janssen and Hansky, clearly demonstrated that the photospheric granulation consists of a pattern of bright granules mostly 1–2″ in diameter, separated by lanes of darker material. However, although Chevalier devoted much effort to the study of the granulation, his work added little to the existing knowledge of its properties. In fact, Chevalier's claim to recognition rests more on his contributions to the study of the fine structure of sunspots than on his work on the granulation.

As a result of the pioneering photographic observations of Janssen, Hansky, and Chevalier, by 1914 the existence and nature of the photospheric granulation was firmly established. However, the time was not yet ripe for a proper physical interpretation of the phenomenon. For example, Chevalier was content to conclude a paper on the photosphere published in *The Astrophysical Journal* in 1908 in the following vein:

> Let us admit ... that the granules are the summits of a fleecy stratum of condensed particles, with or without any horizontal movement; and that the stratum is subject to undulatory movements; the summits of the waves will then present the same succession of changes, their relative position varying in every direction and with any velocity. The short, quickly changing waves of a choppy sea may possibly give us a faint imitation of what is realized on a gigantic scale and in a very different element in the solar photosphere.

Despite their achievement in removing any doubt possibly remaining as to the existence and form of the granulation pattern, Janssen, Hansky, and Chevalier failed to exploit the full potentialities of high-resolution photography. Moreover, they did not realize just how much physical information could be gained from observations of this kind. In fact, nearly half a century was to elapse before the new technique, in an improved form, was fully utilized as a research tool for the study of the solar photosphere (see Section 1.6).

1.3 Strebel's discovery of the polygonal nature of the granules

Following the pioneering work of Janssen, Hansky, and Chevalier, interest in high-resolution photography of the photospheric granulation waned and it was not until 1933 that an important new observational discovery was announced. This came as a result of the efforts of a German physician and amateur astronomer, Hermann Strebel (1868–1943), who, in collaboration with a technician, B. Schmidt, photographed the granulation with a 35-cm horizontal reflecting telescope belonging to the Munich Observatory, diaphragmed down to 20 cm. Amongst other things, Strebel paid particular attention to the important question of the true shape of the granules and reached the conclusion, to quote his own words, '*daß tatsächlich die Granula der Hauptsache nach polygonale Gebilde sind*, daß selbst ausgesprochene Dreiecksquerschnitte häufig vorkommen' (in translation: '*that the granules are actually in the main polygonal structures*, and even definitely triangular structures frequently occur'). The polygonal outlines of the granules are clearly evident on some of the photographs published by Strebel, the best of which show areas where the resolution is, in fact, comparable to that of good modern photographs (see Section 2.3.1).

Strebel's observations demonstrated more clearly than ever before the striking resemblance of the photospheric granulation to an irregular, cellular *convection pattern*. However, Strebel's discovery, despite its importance and its publication in a well-known international journal (*Zeitschrift für Astrophysik*), apparently attracted little attention and, as the years passed, was largely forgotten. In fact, as we shall see in Section 1.6, the irregular, polygonal character of the granulation pattern was not re-discovered until 1957, when photographs of the photosphere were for the first time obtained with a resolution surpassing that achieved by Schmidt and Strebel a quarter of a century before.

1.4 Identification of the granules as convection cells

The essential foundation for the modern convective theory of the origin of the photospheric granulation was laid by the distinguished German astrophysicist Albrecht Unsöld, who in 1930 showed that, as a consequence of the increase in hydrogen ionization with depth, there must exist a zone of convective instability directly beneath the visible photospheric layers. As we shall explain in more detail in Section 5.2.1, an elementary volume of gas moving upwards through the hydrogen ionization zone is heated by the release of ionization energy. The buoyancy of the element is thus increased and it continues its upward journey. In this way convection currents are generated, to which Unsöld attributed the origin of the photospheric granulation (and, incidentally, of sunspots as well).

Unsöld himself did not attempt to give any detailed picture of the exact mechanism involved, but this task was soon taken up by other workers. In 1933 H. Siedentopf (1906–63) suggested that the granules represent globules or bubbles of hot gas pushing their way upwards through cooler descending