Solar Activity: The Role and Necessity of Optical Space Observations in Solar Physics

K. O. Kiepenheuer

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III. SOLAR ACTIVITY

The role and necessity of optical space observations in solar physics

By K. O. Kiepenheuer
Fraunhofer Institut, Freiburg i.Br., Germany

It is shown that, for a quantitative investigation of the physical processes producing the chromospheric structures, an angular resolution of 0.2″ in the extreme u.v. as well as in the magnetic field measurement is indispensable. The same requirements also apply to the study of the primary flare process. The realization of such complex optical space projects will need the integration of ground, balloon and space work.

There are three new possibilities for solar research when working in space outside the Earth's atmosphere: (*a*) *In situ* measurements of physical parameters like particle density and motion, magnetic fields, etc.; (*b*) the extension of optical observation into the extreme u.v. and infrared; and (*c*) the improvement of the telescopic angular resolution for all wavelengths and undisturbed by the inhomogeneities of our own atmosphere. The extension of wavelength range has been practised in the last two decades with the greatest success. For a ground-based solar astronomer, used to working with telescopes of reasonable angular resolution, it is quite astonishing to see how these observations in the extreme u.v., obtained with no angular resolution at all or at least, astronomically speaking, with a very modest one, have supplied us in many cases with quite detailed information.

Practically one can speak of three domains of angular resolution in solar space work. In some projects it is already important to separate the extreme u.v. emission coming from different active regions on the Sun. This implies resolution of a few minutes of arc. If, for example, an X-ray flare has to be localized within an active region, a resolution of 10 to 20″ might already be quite valuable.

If the basic physical structure of the solar atmosphere is to be investigated from space, such that our knowledge obtained on the ground can be completed or supplemented, an angular resolution of definitely better than 1″ will be needed. Most of the individual physical processes, altogether forming the solar atmosphere, occur almost all within dimensions of $\lesssim 1''$. In order to study them a resolution of at least 0.2 or 0.3″ seems appropriate. In this paper we will mostly deal with this domain of resolution.

The potential gain of angular resolution in space through observing outside the disturbing atmosphere has not yet been exploited, either in the extreme u.v. or in the visible. This is certainly largely due to the great technological difficulties involved in such projects. But it is also a consequence of the fact that it has not yet been commonly recognized that even the interpretation of the solar atmosphere as a whole can be based only on non-averaged physical data (density, temperature, velocity, magnetic field, etc.) which, as we know today, fluctuate noticeably within 1″ almost everywhere.

The need for the use of extraterrestrial optical facilities with high resolution in solar research can probably be best demonstrated by discussing the observational problems connected with the interpretation of the dynamics of the chromosphere and of the basic flare process. There can be no doubt that in this field of research at the moment the tools of the theoreticians are ahead of and superior to the tools of observation.

CHROMOSPHERE AND CHROMOSPHERE–CORONA INTERFACE

The chromosphere

Seen as a whole the chromosphere represents the transition between the photosphere with a temperature of about 6000 K and the corona with about 1×10^6 K. Ignoring the inhomogeneous structure of the chromosphere, its average temperature gradient with height would amount to about 200 K/km. As the observations—mostly in Hα—have shown, the chromosphere consists predominantly of structures—spicules, mottles, threads, etc.—which all have dimensions of around 1000 km or less and are imbedded in the coronal plasma.

The analysis of high resolution filtergrams in various parts of the Hα line makes it quite probable that there is almost no absorbing material, no neutral hydrogen, in between these structures.

Along the borders of the supergranules these structures are mostly spicules (visible in the wings of Hα), while the rest of the supergranule cells is covered with thread-shaped structures (as seen in the centre of Hα). All these structures, which fill a considerable fraction of the chromospheric space, are in direct contact with the coronal plasma. They all are surrounded, like prominences, by a thin transition region with a temperature gradient $>$ 500 K/km.

It would imply, furthermore, that the coronal plasma reaches at least down to the lower ends of chromospheric structures about 1000 or 2000 km above the photosphere. This, however, would result in a much too high radio brightness of the Sun (see, for example, Beckers 1968). The radio data, on the other hand, are based on an average atmosphere.

In any case, there can be no doubt that the chromosphere represents a region where coronal and chromospheric plasma interpenetrates everywhere, with a scale length which is probably below 1000 km. The thermal and density structure of this interpenetration region is essentially defined by four factors: the heating of the coronal plasma by the mechanical energy flux emerging from the photosphere; the permanent formation and decay of chromospheric structures; the photospheric magnetic field; and the heat flux conducted downward into the chromospheric region from the corona. The latter is—according to Kopp & Kuperus (1968)—strongly guided by the lines of force and therefore the energy is channelled into regions of enhanced magnetic field. In undisturbed areas these are the boundaries of supergranular cells.

Kuperus & Athay (1967) have tried to show that the conductive heat flux from the corona can by no means be dissipated in the chromosphere–corona interface only in the form of radiation, and suspect that an essential part of it will be transformed into mass motion which they identify with the chromospheric spicules.

Assuming that the conductive heat flux is focused by the magnetic field into lanes of about 2″ width around the supergranules, a flux of about 1 kJ m^{-2} s^{-1} would be available for this purpose. The flux of kinetic energy within an individual spicule, $\frac{1}{2}\rho v^3$, on the other hand, amounts also to about 1 kJ m^{-2} s^{-1}.

It is somewhat difficult to see how this heat engine, transforming heat into directed motion, can have such a high efficiency. Apart from such more general energy considerations, there is really very little known about the physical mechanism, which is basically supposed to produce the chromospheric structures. There are no ground or space observations yet available which allow us to decide clearly whether the spicules—and with them probably also the many other chromospheric structures—are directly or indirectly a product of granular convection in a magnetic field or are exclusively—without help of the granules—produced by the downcoming coronal heat flux. Beckers (1968) has shown that the birth rate of spicules (number of structures visible in a certain area divided by their life time) is about the same as for granules, at least within a typical (rosette) configuration of spicules. Also diameter and life time of a spicule roughly compare with those of a granule. Also from the inspection of high resolution filtergrams, obtained in the wing of Hα and showing at the same time chromospheric structures and photospheric granulation, it seems that spicules and granules could well be related individually (Kiepenheuer 1968).

If spicules form in the coronal plasma they would represent cooled condensations or densifications. If they turned out to be of intergranular origin, they would be a kind of ejection.

The birth of chromospheric structures or the origin of the chromosphere as a whole is a process which involves essentially magnetic fields (in disturbed as well as in undisturbed regions of the Sun!), photospheric convection and the coronal plasma. The basic physical processes occur within volumes of dimensions $\lesssim 1''$. In order to get full information about all components involved in this process, simultaneous observations in the extreme u.v. and in Hα (or better in Lα) with a resolution sensibly better than $1''$ will be indispensable. In addition, chromospheric and photospheric magnetic fields should be known at least down to the dimension of a granule.

The spectroscopic analysis of these phenomena, even if only accomplished in the visible range with a resolution of better than $0.5''$ by using balloon or space facilities, would bring us an enormous step forward!

Altogether we have to conclude—despite the enormous amount of information we have got today about the chromosphere—that we do not know the physical process of its formation. In my opinion this is more due to inadequate angular resolution in the visible and in the extreme u.v. than to limitations in theory.

Flares

The physical interpretation of flares is a subject of violent theoretical discussions, mostly because observation has not yet been able to offer sound data either about the primary flare process itself or about the flare environment and its change with time. Here also observations of sufficient angular resolution are missing, in the visible as well as in the extreme u.v., and quite a number of workers, mostly because of this unsatisfactory situation, have found a kind of satisfaction in formulating overall energy balances, mostly comparing the available magnetic field energy with the flares' energy outputs in the form of mass motion, radiation and corpuscular emission, without trying to supply conclusive observational evidence for a specific flare mechanism.

It is generally believed today that the primary flare phenomenon is an acceleration process which occurs in the low corona 20000 to 50000 km above the photosphere and is therefore not observable directly by optical means. The first observable traces of this process are microwave and X-ray bursts, which point to a plasma temperature of $> 10^7$ K. Shortly after or sometimes almost simultaneously with the X-ray burst the optical flash phase is seen in Hα. From the Hα profiles of the emitting structures we must conclude that they have a density of 3×10^{13} to 10^{12} electrons/cm^3 and a temperature of about 10^4 K, while they are embedded in a plasma of

$> 10^7$ K with only 10^{11} electrons/cm^3. The emitting structures (knots, threads, filaments) must have dimensions < 100 km and fill only a small percentage of the macroscopic flaring volume. It is not quite certain whether these Hα-flash structures occur at the place of the acceleration process or whether the formation and emission of the Hα structures is produced by some hydromagnetic action propagated along the lines of force to some other place. It is not at all clear yet whether these 'cold' structures imbedded in a hot plasma are densified from the coronal plasma alone, or whether they are formed out of preflare prominence-like features. No theory has yet given a convincing explanation of this dual and micro-character of the flare process. No observations of the necessary spatial finesse are available to prove or disprove any such theory.

There is, furthermore, a general belief that the magnetic field—its strength and even more so its configuration—is primarily responsible for the form, history and energy output of a flare. Flares occur preferentially in complex magnetic regions, where opposite polarities intermingle frequently. They start very near to the demarkation line between opposite polarities. According to Severny (1968), in 22 out of 25 flares this distance was less than 9″ ($\sim$ 7000 km), where the horizontal gradient of the longitudinal field is large, often > 10 μT/km (0.1 G/km). This would correspond to *ca.* 10 mT (100 G) across one granule. Macroscopically speaking the primary flare event seems to occur in a *horizontal* field quite in contrast to the well-known theoretical model of a neutral sheet formed by the encounter of two magnetic fields of opposite polarity. The magnetic field at the place of the primary flare event cannot be measured. The field of the photospheric underground whose structure and variation with time is of crucial importance for the physical interpretation of the flare can be recorded up to date with a resolution of a few seconds of arc at best. When it comes to comparing the pre- and post-flare photospheric field configurations, the available resolution is even less. It is true, as Veeder & Zirin (1969) and others have shown, that the study of the chromospheric fine structures such as mottles, threads, etc., which are lined up with the field will be of considerable help, but they give only field directions and not the field strength, and their observation just in the very vicinity of the flare is handicapped by the flare's brightness.

The prospects of getting sensibly better and more conclusive magnetic observations from the ground are not too good. An improvement will definitely be achieved, if the field configuration is no longer obtained by scanning the area around the flare, point by point, but by using a technique which gives the complete field configuration simultaneously. In this case the probability of hitting a moment of good visibility is very much greater than for a scanning procedure covering a time interval of many minutes. It is, furthermore, to be hoped that the fast and irresistible development of image tubes will enable us in a few years to obtain—at least during short intervals of good visibility—magnetograms of a resolution approaching 1″.

A number of more recently obtained non-scanning magnetograms (Lockheed and Aerospace Observatories) using Leighton's technique or replacing the spectroheliograph by a narrow Lyot type filter have already been quite successful and in at least some cases have given an effective resolution better than 2″ (Ramsay 1969). Because of the impossibility of coordinating ground and space observations to better than 1″, the ideal observational approach for covering all physical parameters would doubtless be, just as in the case of the chromosphere, the *simultaneous* observation from space (i) of the primary flare process or its first traces in the extreme u.v., (ii) of the magnetic field structure and the motions in the flare's vicinity and (iii) of the Hα (or Lα) and white light structures of the flare and its photospheric and chromospheric surroundings.

Such requirements, by the way, do not only apply to those flares which Friedman (1969) believes to be only extreme cases of X-ray variability, but also to the rapid variation in the total flux of active regions, especially for $\lambda < 2\,\mathrm{nm}$. Here also the time scale speaks in favour of a microstructure for these events, the interpretation of which calls urgently for their geometrical resolution and correlation with individual visible and magnetic structures. Only then will the internal life, the hydromagnetic meteorology of a coronal condensation and of the chromosphere–corona interface in an active region become understandable. And it is pretty clear that this solar 'micro-world' comprises the observational clues for understanding and very probably also for predicting flares, even if we do not succeed in this decade in resolving the very smallest structures of a flare which might turn out to be as small as 0.05 or even 0.01″!

Observational and technological prospects

In the following the observing situations on the ground, in the stratosphere (balloon astronomy) and in space will be compared, because it is becoming increasingly clear that none of the three modes of access to the Sun can be left out, if the highest possible resolution is aimed at. Steadily improving ground-based observation will always supply the general background for launching more and more complex instruments into space. Ground-based and stratospheric facilities will always play an important role as observing reference, as facilities to perform experiments or as a means of education.

(a) *Ground-based situation*

The impediment to solar observation on the ground from visibility effects is much stronger than commonly expected. Individual pictures of 0.5″ in integrated light, individual monochromatic pictures (Hα filtergrams) and spectra of 0.7″ resolution have indeed been obtained occasionally, but the probability of obtaining time sequences of such documents with the above resolution is practically zero, magnetic field measurements of course included. No doubt, these latter are the most complex observations on the ground and their transfer to extraterrestrial instruments will be especially difficult.

It is perhaps somewhat too early to speak about a glimmer of hope for solar ground observers, that is, the exploitation of the very homogeneous airmasses coming from long distances over the sea, which in terms of temperature fluctuations are 30 to 100 times more homogeneous than corresponding airmasses over land. With the cooperative European project J.O.S.O. (Joint Organization for Solar Observation) we are intensively engaged in evaluating this possibility. In one or two years' time we might be able to give a quantitative answer.

The gain of angular resolution might turn out to be quite striking if compared to the conditions to be found at existing observatories. But after all there is not too much hope, at least for spectra, of improving on the 0.5″ mark on the ground.

(b) *Balloon astronomy*

Up to now only Schwarzschild with his balloon-borne Stratoscope I has been able to photograph the solar photosphere with a resolution of about 0.3″, using an exposure time to $< 0.05\,\mathrm{s}$. Nevertheless, there are good prospects of obtaining also spectra and magnetograms of this resolution, the exposure times of which will be 1000 to 10000 times longer. One of the main handicaps of high resolution work from balloons is the relatively high cost which, for an angular resolution of better than 0.2″ on the Sun, will very probably approach that of a space project. Another difficulty is the limited observing period of 6 to 10 h, connected with a long waiting time for recovery, repair, readjustment and relaunching the instrument as well as the risk of losing it.

These obstacles have seriously delayed the development of this technique and will still do so. The impossibility of timing the complicated launch of such a heavy instrument (weighing 2 tonnes or more) such that, for example, a large flare could be investigated represents another obstacle.

Apart from these complications there will very probably be also a physical limit to the resolution obtainable from the stratosphere in daytime, because of the large temperature differences occurring between the surrounding air and the sunlit parts (mainly the primary mirror) of the instrument. Much can be done of course towards solving these thermal problems, but again this will consume time and a great deal of money.

Altogether the prospect of coordinating high-resolution solar space observations with observations from balloons is limited and should not be overestimated. An improvement of this situation would imply that at least a very modest fraction of space funds would have to be invested in the technology of balloon astronomy which now vegetates, financially speaking, somewhere between space and ground.

(*c*) *Extraterrestrial facilities*

The angular resolution obtained from space vehicles—rockets or satellites—has not yet exceeded 3″ in the domain of solar research. Even the forthcoming first manned ATM project does not promise a better resolution. Nevertheless, the achievement of a much higher resolution even down to 0.1″ plays an important role and presents almost the leading principle for future optical solar research from space in the long-range planning of Nasa or of our colleagues in the United States (see, for example, Nasa Position Paper of the Astronomy Missions Board, July 1969), to a lesser extent also in the European (Esro) planning.

Opinions as to the technological complexity and cost of such solar 'space microscopes' vary enormously among the various experts. Experiences of the last years have shown that not only have the OSO space-craft shown a better pointing accuracy than expected, but also, very unexpectedly, resolutions down to about 2″ have been obtained from rockets (see, for example, Vaiana *et al.* 1968; Tousey, this volume, p. 59).

For the investigation of short-lived physical processes like spicules and other chromospheric structures, flares, moustaches, magnetic knots, etc. it seems adequate and now no longer beyond hope—at least in the brighter part of the extreme u.v. emission spectrum—to use rocket-borne instruments for obtaining resolutions of nearly or better than 1″.

From about 0.5″ resolution on, space telescopes look at something which we will probably never be able to follow from the ground and which therefore we cannot even simulate reliably. In such a case it will be indispensable not only that the extreme u.v. should be observed in space, but that simultaneously and in strict coordination (down to better than the intended resolution) one should also measure the distribution of magnetic field, of motions, and a number of other types of information hitherto obtained only on the ground. The technological requirements for such arrays of space telescopes with their auxiliaries are high: extreme demands on the external and internal stability as well as thermal precautions needed to guarantee the figure of the primary mirror against the effects of solar heat, the complicated operation and maintenance of such a complex multiwave-length instrument and the handling of the great flow of data. Such a project will probably exceed the capacity of a single European nation and as it looks today perhaps even the possibilities of Europe. Nevertheless, we Europeans should not hesitate to enter this field of high resolution work from space, joining as soon as possible the American efforts in this direction or at least developing within this decade as a step toward this goal satellite or rocket-borne instrumentation of intermediate resolution. The scientific and technological field of preparatory work is wide enough for a large number of workers in two continents.

As it looks at the moment, space enterprises of this dimension are no longer discussed as single satellite projects but more and more in association with the manned space station. To guarantee the required high stability of the telescopes, the instrument would have to be used on board a 'free flying module' which then would have to be operated and maintained from the nearby manned space station.

In discussing such high-resolution projects we must not forget that the flux of information per unit area on the Sun (e.g. per square second or minute of arc) will increase by a factor of 2500 when the angular resolution is improved from 5 to 0.1″. But it might well be that the difficulties lie rather in the digestion of the new type of information than in the handling of the larger flux of data which always can be brought down by reducing the observed area on the Sun. In this respect balloon astronomy can be extremely helpful well before obtaining high optical resolution in space. It will teach us how the solar atmosphere—at least in the visible—looks when structures smaller than 0.3″ are included. In this sense balloon astronomy has to take over an important role which, we hope, space planners are aware of. It will give us an opportunity to develop, to test and to handle high-resolution telescopes under rather severe conditions. It will prepare us for impact with the subtelescopic part of solar astronomy.

But we have also to be aware of the danger which lies in putting all our hope on such space instruments of extreme resolution. The long waiting time, which might amount to 10 years, demands that in the mean-time more modest projects—in their resolution exceeding the later OSO spacecraft, however—have to be sponsored and undertaken. Otherwise we risk that solar space astronomers will be lost to other branches of science. This situation could easily arise in Europe.

In this context I would like to come back once more to ground-based solar astronomy. Solar astronomers who will have to learn to build and to use extra-terrestrial observatories of this high resolution have to be educated, and to experiment on the ground. And even if a direct coordination of ground and space observations becomes impossible in the domain of highest resolution there must be a continual and general observational effort on the ground to back up, to follow the accomplishments obtained in space. And this—in my opinion—cannot be reached without creating an *entente cordiale* between space, balloon and ground workers, between space and ground agencies, between space and ground technology. This means also that space funds—to some extent—have to go into ground work. We should not forget that a modern ground-based solar observatory including an extensive effort to select a site according to up-to-date criteria will probably cost only a small fraction of that of a high resolution project in space. But primarily it seems more important to find a new mode of future cooperation between the ground-based and the space astronomer than to mobilize new funds.

CONCLUSION

In order to come to a quantitative physical interpretation of the solar atmosphere, especially of the chromosphere and of the flare process, an angular resolution of < 0.2″ will be absolutely required in the extreme u.v. and in the measurement of solar magnetic fields. This goal can probably be reached only in a number of successive steps and at rather great technological expense. It is doubtful, however, whether extreme u.v. resolutions of 0.5 to 0.2″ can be obtained other than by means of large and costly man-maintained satellites, such as are now under discussion. The recent experiences obtained with rocket-borne spectrographs do not exclude the possibility of finding very much less expensive ways of investigating short-lived processes in the photosphere, chromosphere and corona.

For the realization of high-resolution space projects the role of ground-based and especially of balloon-borne observing techniques becomes increasingly important, whether it be to get optically acquainted with the aspect of the Sun down to the finesse of the photospheric or chromospheric scale or mixing length, to develop and test high-resolution optical technology or even just to keep the profession of solar astronomy alive. In any case an effective help to space projects can be expected only if we succeed in integrating ground, balloon and space work into one unit, at least as far as planning, technology and financing are concerned.

Discussion

A. H. Gabriel (*A.R.U., Culham Laboratories, Abingdon*). With regard to the problem of pointing accuracy, I have heard that the OSO spacecraft is now achieving a figure much better than the earlier predictions. Would Professor Goldberg care to comment?

L. Goldberg (*Harvard College*). OSO–VI has a pointing stability of about 3″ and this can now be taken into account in the design of future OSO experiments.

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