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Future Techniques and Instrumentation in Solar–Stellar Physics*

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Abstract

I review the likely instrumental developments for the study of solar–stellar physics. The study of processes known to exist on the Sun and occurring on stellar surfaces will require increasingly more sophisticated instrumentation and larger telescopes. I specifically describe instrumentation required for the study of stellar activity and activity cycles, stellar rotation, stellar surface motions and magnetic fields, stellar pulsations, stellar chromospheres and coronas and stellar winds.

1. Introduction

Solar–stellar physics as a subdiscipline of astronomy has recently undergone a major revival as techniques for the study of solar-type processes in stars have become increasingly sophisticated. Solar–stellar physics itself is, of course, an old discipline going back at least to the research by George Ellery Hale (see e.g. Hale 1908). Much of stellar observational and interpretational spectroscopy is based on the detailed spectroscopy of the Sun and could therefore be called solar–stellar physics.

What then is solar–stellar physics? I have arrived at three possible definitions: (i) the study of stars from the point of view of *solar physicists*; (ii) the study of physical processes on stars which are of interest to an understanding of the *Sun*; (iii) the study of *stellar physics* in a broader than G2V star context but taking the Sun as a starting point. Although all three definitions are valid, I prefer the latter definition because it views the solar part of the discipline in a much broader context, as an integral part of the field of astrophysics.

The objective of this paper is to describe the likely future development of instrumentation and techniques from this third point of view. The type of physical processes which qualify to be included in this are (i) the study of stellar activity and stellar activity cycles; (ii) the study of stellar rotation; (iii) the study of stellar surface motions and magnetic fields; (iv) the study of stellar pulsations and oscillations; and (v) the study of stellar chromospheres, coronae and winds. In describing each of these topics, I first summarize the techniques used now for stellar observations and the observations in integrated sunlight which couple the properties of the Sun to those of the stars (the so-called 'solar connection'). Then, I will anticipate future developments.

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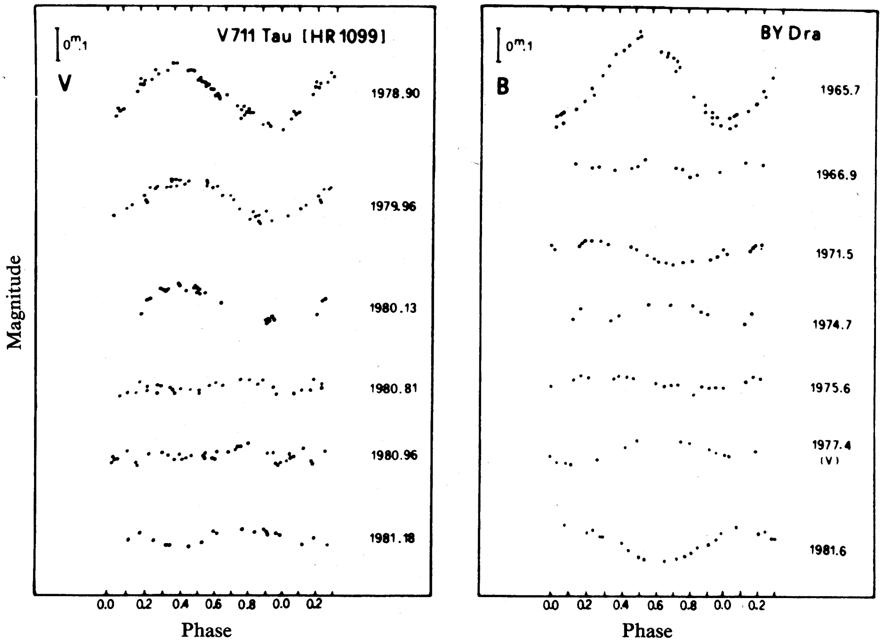

Fig. 1. Photometric variations of the RS CVn system V711 Tau (*left*) and of the flare star binary BY Dra (*right*). The variations of the amplitude and shape of the lightcurve suggest sizable changes in starspot number or distribution.

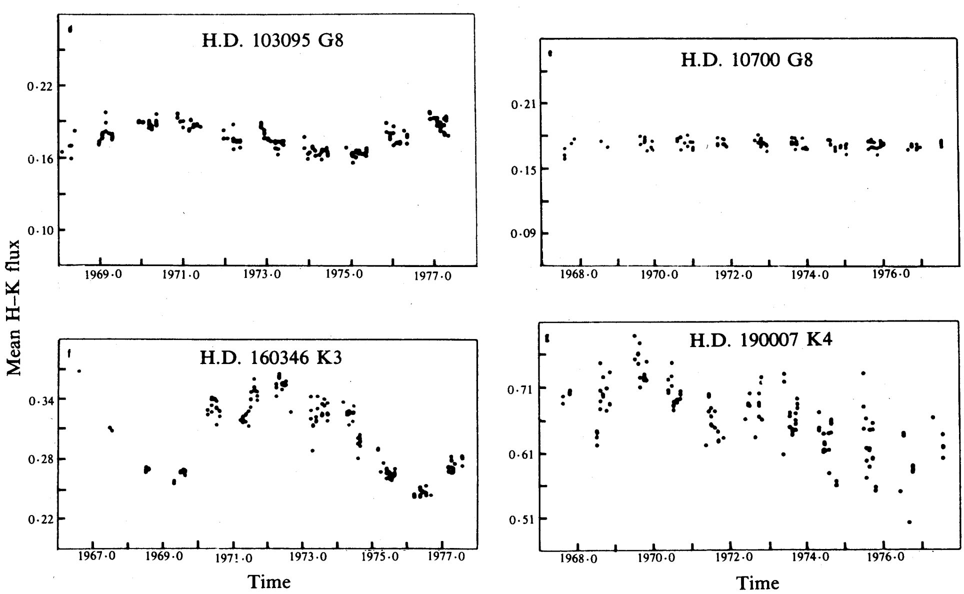

Fig. 2. Mean H and K fluxes for four of the stars monitored by Wilson, plotted versus time from 1967 to 1978

2. Stellar Activity and Stellar Activity Cycles

Stellar activity similar to solar activity can be observed by the effects of the stellar equivalents of sunspots, solar flares and solar plages on the light and spectrum of integrated starlight. The variation of these effects leads to the identification of activity cycles and stellar rotation (see also Section 3).

Summary of present techniques. Starspots have been inferred from small photometric variations of stars (see Fig. 1). Vogt (1982), in a technique which I have called 'Doppler imaging', has been able to track a starspot as it moves across a stellar disc of a rapidly rotating star by identifying the variable effect of the spot on the rotationally broadened spectral-line profiles. Stellar activity has, however, been mostly studied by Wilson and collaborators at Mt Wilson by observing the variations of the central intensity of the Ca^+ H and K lines. Fig. 2 shows the variation of the H and K fluxes as a function of time, illustrating both the effects of stellar activity cycles and of stellar rotation. It is the most powerful tool currently available for the study of stellar activity. The variations in the H and K fluxes are believed to be due to the increased fluxes in stellar plages. Rapid variations in other chromospheric lines (e.g. Hα) in flare stars are similar to the variations seen in solar flares, therefore showing evidence for stellar flares.

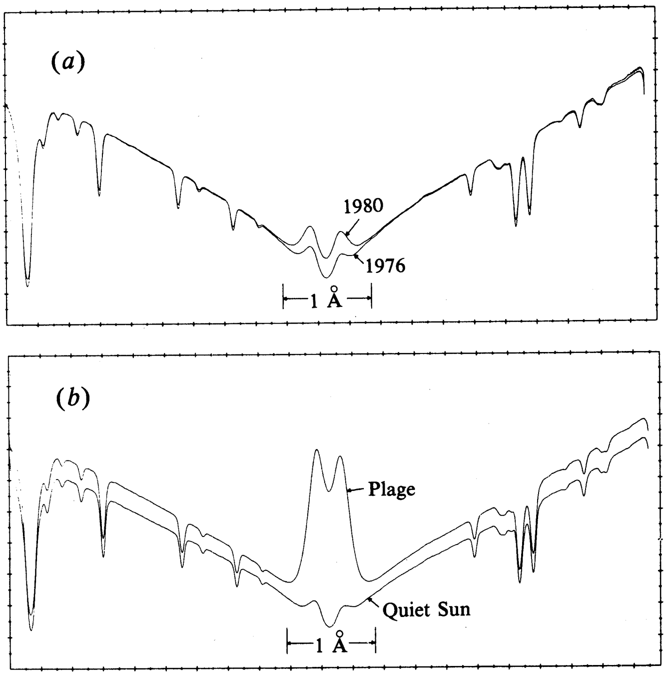

Fig. 3. Variability of calcium K profiles: (*a*) full disc K at minimum and maximum superposed and (*b*) average profiles for an active region (plage) and a nearby quiet region at the same limb distance.

Solar connection. Observations of the variation of the solar constant with the NIMBUS and SMM/ACRIM experiments (Woodward and Hudson 1983) have given the solar equivalent of the stellar photometric variations. The interpretation of the solar data is however complicated by the effects of facular regions. Livingston *et al.* (1982) have studied the solar H and K line spectrum (see Fig. 3) and found significant variation of the H and K line flux as a result of solar activity.

Future instrumentation. With the advent of UV and X-ray telescopes in space (ST, AXAF, etc.) one might expect stellar activity studies to increasingly use the properties of chromospheric, transition region and coronal lines in that part of the spectrum. The Solar Optical Telescope (SOT) scheduled to be launched in 1991 could, for example, spend its night-time part of the orbit observing the behaviour of the C IV lines from stars.

With the new large ground-based telescopes, the imaging of stellar discs through speckle interferometry techniques will come within reach. A 4-metre telescope has an angular resolution (radius of Airy disc) of ~30 milliarcsec, enough to just resolve the diameter of the largest (in angular diameter) stars (except for the Sun), but inadequate to resolve surface structure. The 21-metre baseline National New Technology Telescope (NNTT) will resolve to 6 milliarcsec or ~50 pixels in the disc of Betelgeuse so that surface structure studies, at least for the largest of stars, will become possible. If optical interferometers can be made to image stellar discs this resolution could be much enhanced.

3. Stellar Rotation

Solar rotation appears to be very complex (see e.g. Beckers 1981); indeed, measured from the proper motion of tracers such as sunspots and spectral line shifts different results are obtained. Solar rotation rates not only vary according to the type of tracer used, but also show variations with latitude. Stellar rotation is therefore not likely to be a very well-defined one or two parameter property, at least not below the 10% precision level. Rotation probably varies in the stellar interior as well as with latitude. The relatively meagre amount of information on stellar rotation obtained so far may now grow rapidly as new techniques develop.

Summary of present techniques. The earliest methods of measuring stellar rotation used line profile broadening. These techniques have recently been improved by Gray (see e.g. Beckers 1981) and others using Fourier transform techniques for analysing spectral lines. Precision observations allow the determination of rotation for even rather slow Sun-like stars. Such techniques give only a measurement of the line-of-sight stellar rotation velocity ($V \sin i$), and to derive the stellar rotation period one needs the stellar diameter and the inclination i of the stellar rotation axis. Variations in the H and K line flux (see Fig. 2) and photometric variations (see Fig. 1) directly give the rotation period, as does the proper motion of traces in spectral imaging (see Section 2).

Solar connection. Gray has also analysed the spectrum of integrated sunlight and derived rotation velocities which are consistent with the resolved disc observations. The same has been the case for the H and K profile and flux data by Livingston and White (1982).

Future instrumentation. Variations in UV and X-ray lines and in the continuum can give a determination of rotation periods in stellar envelopes. Interferometric imaging with very large telescopes such as the NNTT will make it possible to study stellar rotation by means of tracers, and is likely to lead to a determination of all parameters involved in stellar surface rotation (e.g. differential rotation, determination of the inclination angle, rotation rate, and projection of the rotation axis on the sky). The technique of differential speckle interferometry (see Beckers 1982) uses the different locations of the photo-centre of gravities in opposite spectral line wings to infer the orientation of the stellar rotation axis projection on the sky. If precise stellar pulsation measurements (see Section 5) become possible so that the rotational splitting of the different modes can be resolved, a determination of the interior stellar rotation will come within the realm of possibility.

4. Stellar Surface Motions and Magnetic Fields

Here we combine the study of surface motions and magnetic fields because they use very similar techniques, relying on the precise observation and analysis of profiles in polarized and unpolarized spectral line observations. The broadening and shape of these lines contains information on stellar surface motions over all scales (even rotation) and on stellar magnetic fields.

Summary of present techniques. Again the Fourier transform analysis is the latest advance in spectral line investigations and results in a determination of the full integrated motion field of stellar surfaces. From the behaviour of lines of different strength, and specifically from the curve of growth analysis, information can be obtained on very small-scale motions (i.e. less than or equal to the $\Delta\tau = 1$ length scale, also called 'micro turbulence'). Robinson *et al.* (1980) and others have recently used a technique (first tried unsuccessfully on the Sun) in which the linewidth is studied as a function of the Landé g factor to devise estimates of stellar surface field

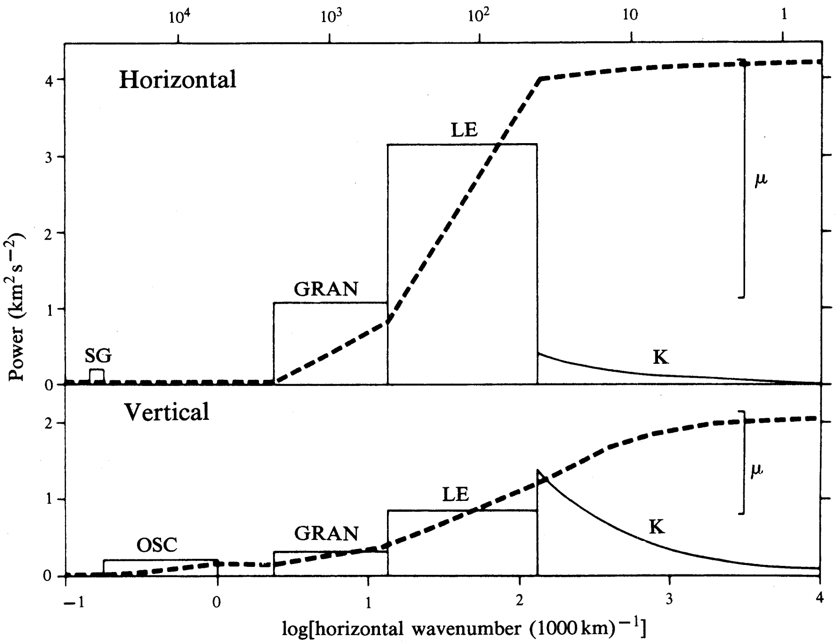

Fig. 4. Size distribution of horizontal and vertical velocities at $\tau_0 = 0{\cdot}1$ in the solar atmosphere, where SG is supergranulation, GRAN is granulation, LE is unresolved convective motion as inferred from the limb effect, OSC is solar oscillation, K is Kolmogoroff-type eddy decay motion and μ is the amount of 'microvelocity' derived from line saturation studies. The dashed curves represent the total motion field above a given scale.

strength. For large stellar surface fields, as seen for example on A_p stars, one can of course make much more detailed studies. With the recognition that solar line profile bisector behaviour is largely due to surface convective motions (Beckers and Nelson 1978), the study of line asymmetries in stellar spectra is becoming of interest.

Solar connection. Again, the interpretation of the spectrum of integrated sunlight provides the stellar connection with solar phenomena. In Fig. 4 (taken from Beckers 1981) the total macroscopic and microscopic velocity field on the Sun is separated into resolved components and into the estimated velocity fields at scales below the angular resolution limits attainable with ground-based telescopes. The granular/convective velocity effects dominate the line broadening. With the SOT much of the as yet unresolved convective motions should be observable.

Future instrumentation. For stellar work the main advance is expected to come from the higher spectro-photometric precision achieved for the large telescopes now being planned. Line profiles obtained in the UV and X-ray regions will teach us about stellar chromospheric–coronal motions.

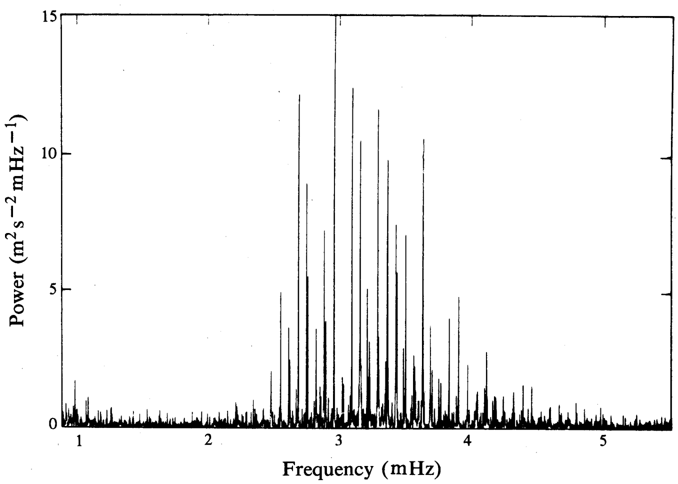

Fig. 5. Spectrum of solar 5 minute oscillations observed over 6 days and obtained at the geographic South Pole by Grec *et al.* (1983).

5. Stellar Pulsations or Oscillations

The recognition that 5 minute oscillations actually reflect the presence of low and high order non-radial pulsations of the Sun has led to a new field of study known as 'solar seismology' or, perhaps, 'solar tomography'. By measuring the properties of the pulsations it will be possible to investigate the solar interior and to measure large scale internal flows such as rotation.

Summary of present techniques. Stellar pulsations have been observed through precision photometry of stars such as ZZ Ceti. Doppler imaging has shown the presence of pulsations in early-type stars. Fossat and colleagues have applied the resonance scattering techniques developed so successfully for solar observations to stellar research and found evidence for pulsations in Procyon and α CEN.

Solar connection. Pulsations in integrated sunlight for radial velocities have been observed by Grec *et al.* (1983) at the South Pole using resonance cell techniques (see Fig. 5). The fine structure seen in this spectrum is resolved extremely clearly and is currently being analysed in terms of the structure of the solar interior. Solar pulsations have also been detected in integrated sunlight by Woodward and Hudson (1983) using SMM/ACRIM data. The profiles of the central H and K lines also have long been known to show solar oscillations and Harvey and others are currently analysing a long series of South Pole data obtained for these lines.

Future instrumentation. The field of instrumental research for applying the techniques used for solar observations to stars is wide open. Precision stellar Doppler shift observations are presently being pursued by a number of groups (e.g. Fossat, Connes and McMillan), and ultimately the shift of many spectral lines will be used to overcome photon noise limitations. Stable wavelength references will be needed to eliminate instrumental drift effects. Parallel to the solar oscillation program, we may see a coordinated effort by ground-based observatories to give a continuous observing sequence of stellar pulsations. The groups of Harvey and of Noyes are now experimenting with H and K line flux photometry techniques to detect stellar pulsations. High precision ($\leqslant 0 \cdot 1\%$) stellar photometry, possibly carried out in space to avoid atmospheric scintillation and transparency variation effects, is another possibility for the detection of stellar pulsations.

6. Stellar Envelopes

We classify all layers above the photosphere as the stellar envelope, which includes therefore the stellar chromosphere, transition regions, coronae and stellar winds, as well as discrete structures like prominences, bulges, rings, discs, etc. Not included in the present definition are stellar dust clouds, although the study of these clouds in solar-type systems and in the interplanetary medium around stars could legitimately be included in our present discussion on solar–stellar physics.

Summary of present techniques. Almost all information on stellar envelopes is obtained from spectroscopy in the optical and UV regions and from variations in X-ray fluxes. Around some stars the envelopes can actually be resolved by speckle imaging techniques (see e.g. Beckers 1985) or even by direct imaging (e.g. Na and K lines around red supergiants).

Solar connection. Spectroscopy of integrated sunlight provides, of course, the necessary connection. This is the essential connection for many of the research areas described here and, as a result, it has greatly expanded in recent years.

Future instrumentation. With the advent of more powerful UV and X-ray space telescopes (ST, SOT, AXAF), which will allow high resolution spectroscopy of stars, major advances in the study of the outer layers of stars can be expected. The perfection of speckle imaging techniques, especially of differential speckle interferometry (Beckers *et al.* 1983), combined with the availability of large ground-based telescopes such as the UC/CalTech 10-metre telescope and the NNTT, should lead to direct imaging of the envelopes around a number of large stars.

7. Conclusions

The rather broad-brush description given here of possible instrumentation in future solar–stellar physics is far from encyclopedic or particularly accurate. It is impossible to exactly predict which instrumentation and techniques are likely to develop and flourish given the rapid advance in this discipline. Although this paper is of limited scope and does not attempt to give a comprehensive review of either the techniques currently used or of the solar connection, it does present one (undoubtedly limited) perception of the status and development in this exciting field of research. Solar–stellar research may very well turn out to be the main source of drive for the renovation and development of stellar photometric and spectroscopic research for years to come. For progress we will need large observatories operating in many regions of the spectrum in space and on Earth, as well as sophisticated measurement techniques to analyse the light collected at these observatories.

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