since only two are known in the LMC. In Fig. 6 I show spectra of 4 very early O supergiant stars in the central part of the cluster very close to R136. I also show in the figure the spectrum of HD 93129A, which according to Conti and Burnichon is the most luminous star in our Galaxy. The 30 Doradus stars shown in the figure have bolometric luminosities similar to HD 9319A (some are even larger)! It is natural to expect more of these stars in R136a, especially if mass segregation effects are important.

At a distance of 53 kpc, 3 arc-seconds correspond to a diameter of about 0.8 pc, large enough to contain hundreds of stars. In fact galactic globular clusters have cores in this range of diameters. But, what about the speckle results?

The speckle interferometry results were obtained at optical wavelengths. As I have shown above, very hot O stars (which dominate the UV flux) are in fact very faint in the visible; as seen by the speckle, a compact group of these stars would not be resolved and may be what the speckle observers have called "complex background". In turn, later type O stars or late WN stars are much cooler and radiate much of their energy at optical wavelengths. This fact is illustrated in Table 1 where the most luminous stars in 30 Doradus in the visual band can be seen to be relatively cool compared to the hottest stars in the nebula. Thus, most likely, the speckle experiments have just detected one or two WN stars in the centre of R136a, probably the stars seen by Innes in 1927. After allowing for seeing effects, Moffat and Seggewiss find that within a diameter of 1.5 arc-second, R136a has a visual magnitude of $V=12.1$ even fainter than some of the stars listed in Table 1. Two of these stars (as seen by Weigelt and Innes) would then make up the optically (but not necessarily UV) brightest component. In order to test this hypothesis, in collaboration with Hernan Quintana from the Universidad Católica de Chile, I have obtained spatially resolved spectra of R136a with the 4 m telescope at CTIO. The slit was 0.5×3 arc-seconds centred in the brightest part (centre) one second of arc north (N) and one second south (S) of this position. Tracings of these spectra (each corresponding to an average of 8 Vidicon frames) are shown in Fig. 7. The spectrum is seen to vary significantly from north to south, particularily the emission line component (disregard the changes in the continuum which are due to atmospheric refraction. Also the zero point of the continuum has been shifted to separate out the components) changing from WN4.5 in the centre and N to WN7 in south. The asymmetry of the He II λ 4686 line may be due to absorption lines from early O-type stars (this is most prominent in S) which would imply that the O component of R136a is dominated by main-sequence stars.

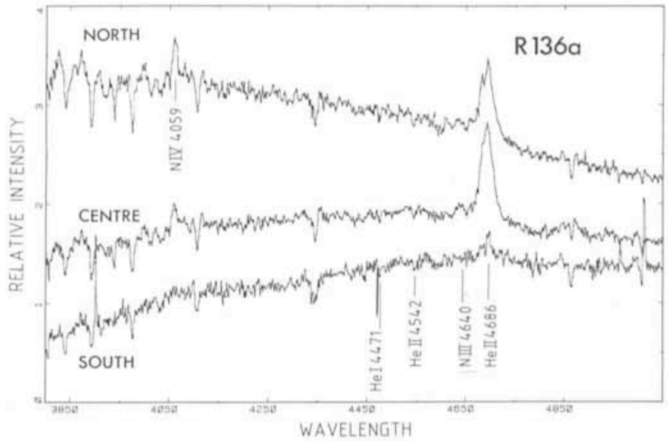

Fig. 7: *Spatially resolved spectrograms of R136a taken with a slit 0.5 arc-second wide and 3 arc-seconds long. The offset between centre and north or south is one arc-second.*

Epilogue

R136 is clearly the unresolved core of the ionizing cluster of the 30 Doradus nebula. It contains many very hot O stars which account for the observed UV luminosity and effective temperature. R136 also contains several late-type WR stars which account for the observed optical and infrared properties. The visually brightest of these WR stars, R136a, is the star (or 2 stars) found by the speckle interferometry. The luminosity, colour and infrared properties of this star are similar to that of other bright WR stars in the nebula. Most of the radiation required to ionize the nebula is emitted by stars outside R136. R136 itself contributes less than 30 % of the ionizing flux.

In their recent preprint, Moffat and Seggewiss, using data complementary to those I have presented here, reach the same conclusion regarding the nature of R136a.

References

To make the text easier to read, I have not included formal references. Complete references to most of the papers I have mentioned can be found in the article on R136a by Schmidt-Kaler and Feitzinger published in the proceedings of the ESO conference "The Most Massive Stars". All other articles I refer to are preprints kindly sent to me by the authors.

Stellar Granulation and the Structure of Stellar Surfaces

D. Dravins, Lund Observatory

Convection in Stars

Stellar convection is a central but poorly understood parameter in the construction of stellar models and the determination of stellar ages, influencing both the energy transport through the atmosphere and the replenishment of nuclear fuels in the core. The motions in stellar convection zones probably supply the energy for generating magnetic fields, heating stellar chromospheres and coronae, driving stellar winds, and for many other nonthermal phenomena. The inhomogeneous structure of velocity fields on stellar surfaces complicates the accurate determination of stellar radial velocities. Further, the temperature inhomogeneities on stellar surfaces induce molecular abundance inhomogeneities and entangle the accurate determination of chemical abundances.

New diagnostic tools are now making stellar atmospheric convection accessible to direct study. From solar physics has come the realization that effects from solar granulation (Fig. 1) are visible also in the spectrum of integrated sunlight, i.e. the Sun seen as a star (Dravins et al. 1981). Consequently, also the effects of stellar granulation should be visible in stellar spectra. Theoretical models of inhomogeneous atmospheres, incorporating three-dimensional, radiation-coupled, time-dependent hydrodynamics of stellar convection, have been

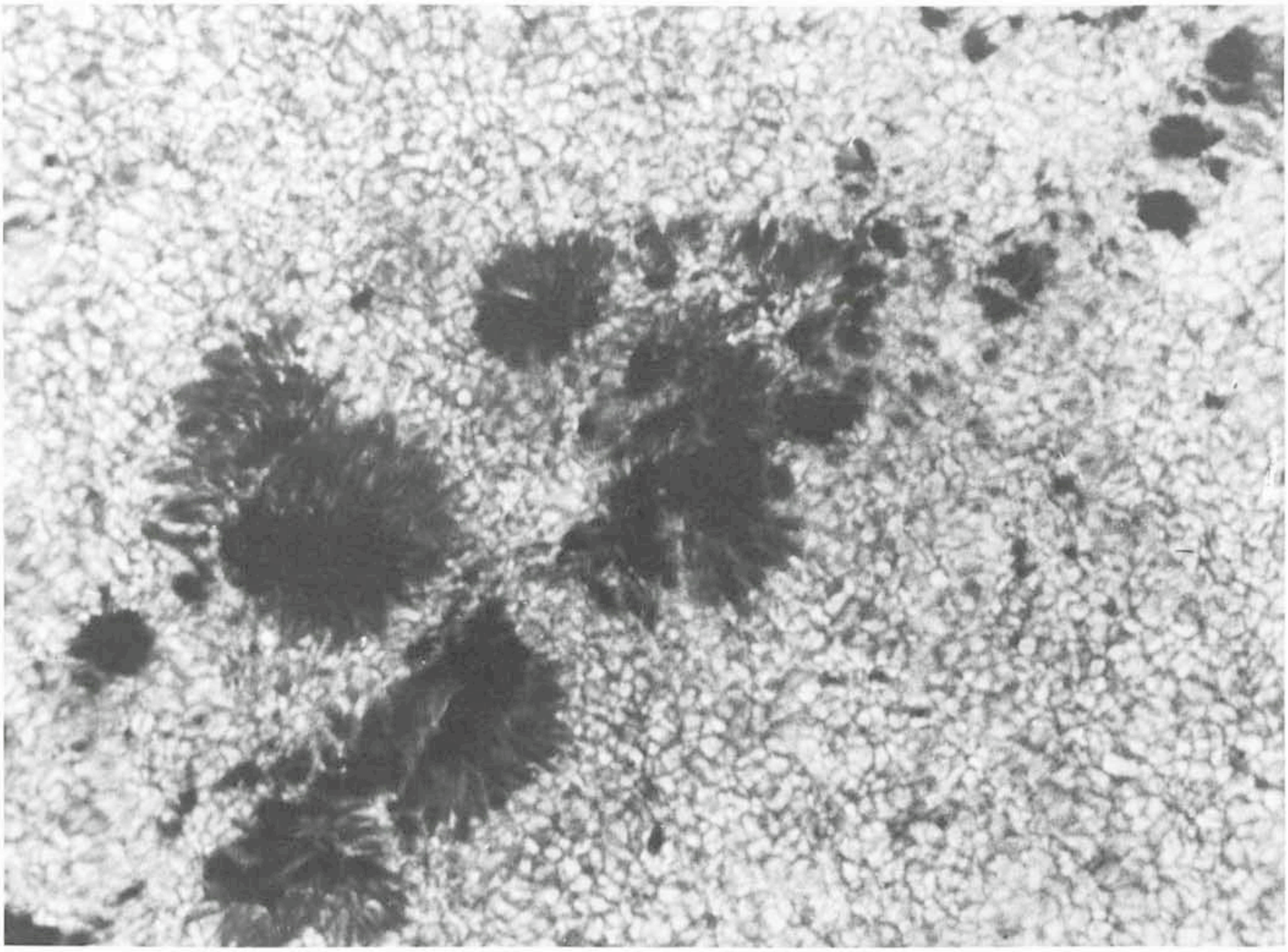

Fig. 1: *The solar surface gives a hint of what stellar surfaces may look like. In this white-light photograph, the convection cell pattern of solar granulation is prominent outside the dark sunspots. The effects of granulation are also manifest as subtle effects in the spectrum of the Sun seen as a star, and the corresponding phenomena in other stars are now being studied with the new coudé echelle spectrometer on La Silla. This photograph was recorded by G. Scharmer with the Swedish solar telescope on La Palma.*

developed and have successfully reproduced observed solar properties (Nordlund 1978, 1982). Work is now in progress to extend this to other stars. Taken together, these methods promise to open up stellar convection and stellar atmospheric inhomogeneities to detailed investigation (Dravins 1982a).

Such studies, however, are rather demanding, both on the observational and on the theoretical side. Granulation causes only rather subtle spectral line asymmetries, amounting to equivalent Doppler shifts of only some hundred m/s (Fig. 2). The measurement of such line asymmetries requires stellar spectra of much higher quality than has ordinarily been available. For each computation of a theoretical hydrodynamic model atmosphere, skilfully programmed codes require several hours for each run, even on very large and very fast computers such as CRAY or CYBER. However, the increased availability of powerful spectrometers and computers alike promise to make the study of stellar surfaces a fruitful one in the years ahead.

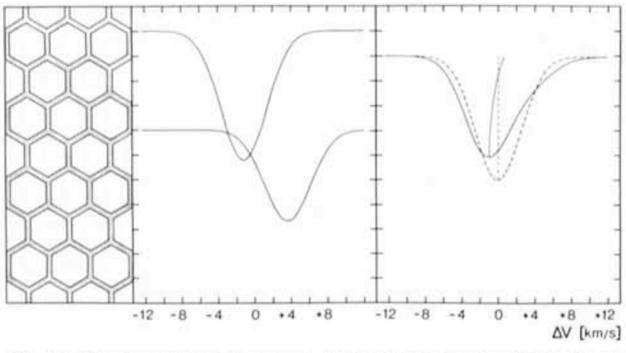

Fig. 2: *The correlation between temperature and velocity in stellar convection (hot elements are rising) causes slight asymmetries in photospheric absorption lines. In this model illustration, 75 % of the surface of a solar-like star is covered by bright areas of hot and rising gas, balanced by the downflow of cooler gas over the remaining 25 % of the surface (left). Spectrally blue-shifted profiles from hot, bright and rising elements contribute more photons than the darker, cool and sinking ones (centre). The resulting line profile, after averaging over the stellar surface, becomes asymmetric (solid curve at right) and its "C"-shaped bisector (median) demonstrates the asymmetry of the line. The dashed curve shows a classical symmetric profile, characteristic of classical stellar atmosphere concepts, dealing with homogeneous atmospheres containing turbulence only and without any organized velocity patterns.*

The ESO Coudé Echelle Spectrometer

At ESO on La Silla, an important new instrument has recently gone into operation, which permits one to obtain spectra of the required quality. This is the coudé echelle spectrometer (CES), primarily fed by the 1.5 m coudé auxiliary telescope, but also accessible for the 3.6 m telescope via a fiber optics link. The progress of this instrument during its development has been reported in the *Messenger* by its main designer D. Enard (1977, 1979, 1981).

The CES is an instrument for the study of spectral line profiles. In its commonly used setup, it uses a multi-element detector, e.g. a Reticon diode array. This gives a very convenient way to obtain low-noise spectra of extended spectral regions, combined with high sensitivity. The spectral resolution ($\lambda/\Delta\lambda$) obtainable is about 100,000, corresponding to a Doppler shift of 3 km/s. Although this represents, by stellar standards, a very high resolution, it is still insufficient for serveral applications.

Actually, a lot of exciting phenomena in modern solar physics are studied from spectra featuring resolutions of up to one million. Further, such spectra are often recorded with Fourier transform or double-pass grating spectrometers with signal-to-noise ratios of the order of 1,000 : 1. Such low noise levels are not possible with any normal stellar spectrograph, irrespective of the detector used or the brightness of the star. Limitations arise because the optical construction of conventional stellar spectrographs, in the interest of light efficiency, does not sufficiently suppress stray light, which then contaminates the observed spectrum. Origins of such stray light may be e.g. diffuse scattering on optical surfaces or grating ghosts from a diffraction grating.

The Coudé Echelle Double-Pass Spectrometer

The CES incorporates a facility to allow observations of extremely high quality of selected spectral lines in very bright stars. It is possible to operate it as a double-pass scanner, a mode similar to that of several spectrometers used to record solar spectrum atlases. A double-pass spectrometer is characterized by the light passing the grating twice. After a first pass, a normal focused spectrum is formed inside the instrument. In a conventional system, the detector would have been placed at this point. However, in double-pass operation, the desired spectral element is transmitted through a narrow slit, while all other light is blocked off. The light is then sent back to the grating a second time to verify if really all of it is of the correct wavelength. Parasitic light of other wavelengths will not pass this test, and will not reach the exit slit to be detected by the photomultiplier. This forms a very efficient way of reducing stray light: the instrumental profile is, in effect, squared. If the straylight amplitude at some distance from the correct wavelength in conventional single-pass operation is 10^{-3}, say, in double-pass it will be down to 10^{-6}. Although the amplitude of stray light at any one point on the instrumental profile may appear small, the accumulated effects may cause a surprisingly large deterioration of spectral line parameters because stray light at any point in the spectrum is contributed from all other wavelengths. It was only after the introduction of double-pass spectrometers in the 1960s that the true shapes and depths of solar spectrum lines became known.

In addition, the CES double-pass mode doubles the dispersion and the spectral resolution since the set-up is equivalent to two identical echelle spectrometers in series. Consequently, recording of stellar spectra is possible with resolution $\lambda/\Delta\lambda$ of about 200,000. Further advantages include: uniformity of response and absence of pixel-to-pixel variations (since one and the same detector is measuring all spectral elements), and also constancy of focus and optical aberrations across the spectrum (assured by the placement of the fixed exit slit on the optical axis). The spectrum is scanned in wavelength by rotating the plane grating on its turntable. This scanning is done rapidly (typically 4 cycles per second) to reduce effects of atmospheric seeing variations.

Altogether, the CES double-pass system permits a superior recording of stellar spectra. Unfortunately, its high performance also carries a high price in photons and in observing time. Since only one spectral element is measured at any one time, the required observing times are much longer than for multi-element detectors. Nevertheless, it is an ideal instrument for the study of line shapes in the spectra of very bright stars (Fig. 3).

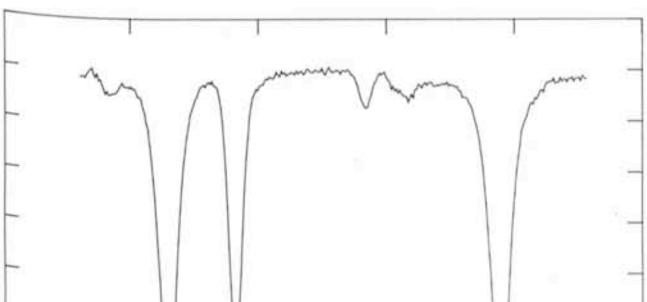

Fig. 3: *The coudé echelle spectrometer in its double-pass scanner mode can record stellar spectra with a fidelity that begins to be comparable to that in solar spectrum atlases. Here, a group of Fe I lines are seen in Alpha Centauri A, recorded with a nominal spectral resolution of more than 200,000. The numbers indicate approximate wavelengths in nanometres. The bisector for the leftmost line appears in Fig. 5.*

How to Detect Stellar Granulation

For several years, we have been working towards the goal to detect and study stellar granulation. Different high-resolution observations have been collected since 1975, and various feasibility studies carried out. For example, stellar observations have been simulated by convolving a solar spectrum atlas with instrumental profiles determined for actual stellar spectrographs, and the resulting spectrum analyzed. During the course of such studies, it was realized that the problem was more difficult than originally envisioned. The main obstacle is the presence of systematic (rather than random) errors in stellar data. Even a spectrograph resolution of 100,000 will perceptibly degrade the subtle asymmetries expected to be present in the spectra of solar-type stars. (Line broadening in even rather slowly rotating stars will cause a similar degradation.) Scattered light from distant wavelengths will induce fortuitous asymmetries, as will even symmetric instrumental profiles (because the stellar lines are asymmetric to begin with). In addition, the lines to be studied must be, as far as possible, free from blends. Merely to select candidate lines for detailed study requires an atlas-type high-resolution spectrum for each star in the programme.

To verify the ability to detect authentic line asymmetries, stellar spectrometers were used to perform observations of the Sun seen as a star. Such an observed spectrum can be checked against a standard spectrum of integrated sunlight, recorded with a more powerful spectrometer (Beckers et al. 1976). In the case of observations with the CES, integrated sunlight can readily be obtained by pointing the coudé auxiliary telescope at the sunlight-illuminated dome of the 3.6 m telescope.

The analysis of such spectra gives a credible method to verify and optimize observing and reduction procedures, and to make the crucial solar-stellar connection. Fig. 4 shows these steps from solar to stellar photospheric line asymmetries. The bisector for the solar line, as measured by the CES, is reasonably similar to the "true" bisector from the Sacramento Peak atlas, and the sense of the small systematic deviation is consistent with the degradation expected from the lower resolution of the CES. The criticalness of the observations is illustrated by the noise bumps on the bisector that are well visible although, in the spectral continuum, more than 180,000 photons were accumulated in each 0.0013 nm (13 mÅ) wide channel. Similar observations have been made using different resolutions, different detectors and different spectrographs, confirming that the CES in double-pass with its highest spectral resolution yields the most truthful line bisectors. Although the CES is thus adequate to begin studies of stellar surface structure, it is not so by any wide margin.

Stellar Line Asymmetries

In our programme to search for photospheric line asymmetries, several brigth stars have been observed. In Fig. 5, samples of representative bisectors for lines in four stars are shown, illustrating the diversity of line asymmetries encountered. Lines in Canopus have a depressed blue flank close to the continuum, which accounts for that bisector's sharp turn towards shorter wavelengths. Possibly the line shape in this giant star may be influenced also by effects such as the atmospheric transition to stellar wind expansion. The asymmetry of lines in Arcturus is essentially opposite to that in the Sun, as noted already by Gray (1980, 1982).

The Structure of Stellar Surfaces

The shape of photospheric line bisectors is very sensitive to the detailed structure of stellar atmospheric inhomogeneities and convective motions, making bisectors a useful diagnostic tool to probe stellar surfaces. The most characteristic property of solar-type bisectors, their "C"-shape (Fig. 4) is caused by the vertical asymmetry of the granular velocity field (Fig. 2). An idealized way to see this is to consider the case of a very narrow line profile everywhere on the stellar surface. The spatially averaged profile then has the shape of the distribution function for the vertical velocities, e.g. a Gaussian in the case of Gaussian motions, etc. On the Sun, the relatively larger downward velocities in the intergranular lanes cause a distribution function with an extended "red" tail, which is the main cause of the upper redward bend of the bisectors. This characteristic solar property vanishes for a velocity field that is symmetric with respect to up and down. The line asymmetry becomes inverted if one instead has small granules with concentrated upward velocities, surrounded by larger areas of relatively gentle downflows. In such cases, the result is a ")"-shaped bisector, such as seen for Canopus (Fig. 5), and sometimes also observed over small areas on the Sun.

Spectral lines of different excitation potentials show different types of bisector, because different lines predominantly form in different surface inhomogeneities, e.g. the highest-excitation lines form mainly in the hottest elements. Lines in different wavelength regions will also show different bisectors because the relative brightness contrast in granulation (caused by a given temperature fluctuation in a blackbody radiator) decreases with wavelength, and thus changes the relative photon contributions from the hotter and the cooler elements.

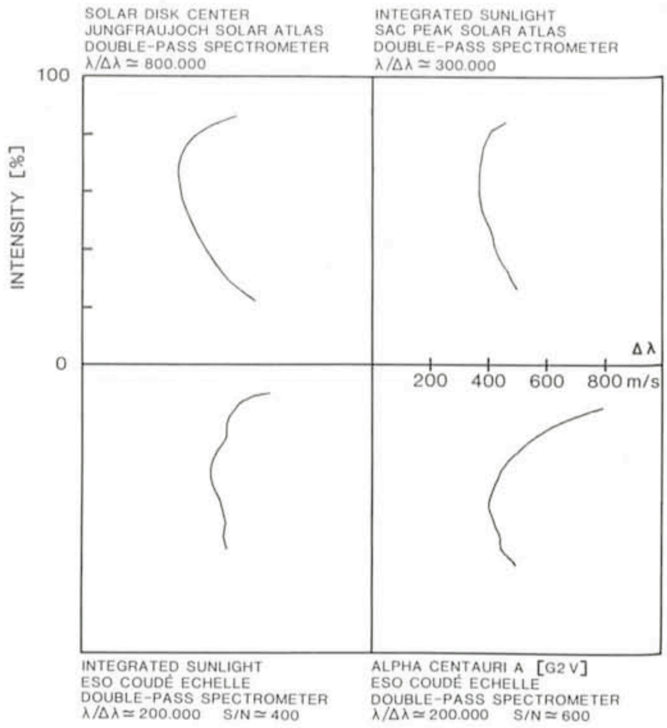

Fig. 4: *Observational steps towards stellar granulation. The asymmetry of an apparently unblended Fe I line is represented by its bisector (cf. Fig. 2), which shows the apparent radial velocity measured at different intensity levels in the line. For the Sun, the asymmetry is most pronounced at solar disk centre (top left), and somewhat less so in integrated sunlight (top right), because of e.g. line broadening due to solar rotation. At bottom left the same line of integrated sunlight is seen, as observed with the ESO coudé echelle spectrometer, confirming that instrument's ability to detect these subtle asymmetries. At bottom right is the same line in Alpha Centauri A. Although this star is of the same spectral type as the Sun (G2 V), it is actually somewhat more luminous and lies in the upper part of the main-sequence band in the HR diagram. The more pronounced asymmetry of this line in α Cen A might suggest more vigorous convection in this slightly evolved star that is clearly older than the Sun.*

For the Sun, such bisector behaviour has been studied, and it can be at least qualitatively understood from hydrodynamic model atmospheres (Dravins et al. 1981). For stars, such studies for different classes of lines are just beginning (Dravins and Lind 1983, Gray 1983).

Direct Observations of Stellar Surfaces

The probing of stellar surfaces through photospheric line asymmetries is, after all, only an indirect method that rests upon an extrapolation from solar conditions. In stars very different from the Sun, novel surface phenomena may well appear, e.g. in some stars the convection cells might be destroyed by "sonic boom" shock waves, generated when convective velocities reach the speed of sound. In cool stars, dust clouds might condense over the coldest surface formations. Quite possibly, our current understanding about stellar surfaces is even more naive than was our understanding about planets and moons before their exploration by spacecraft. To remedy this will ultimately require spatially resolved images of stellar disks and spatially resolved spectra for different parts of stellar surfaces.

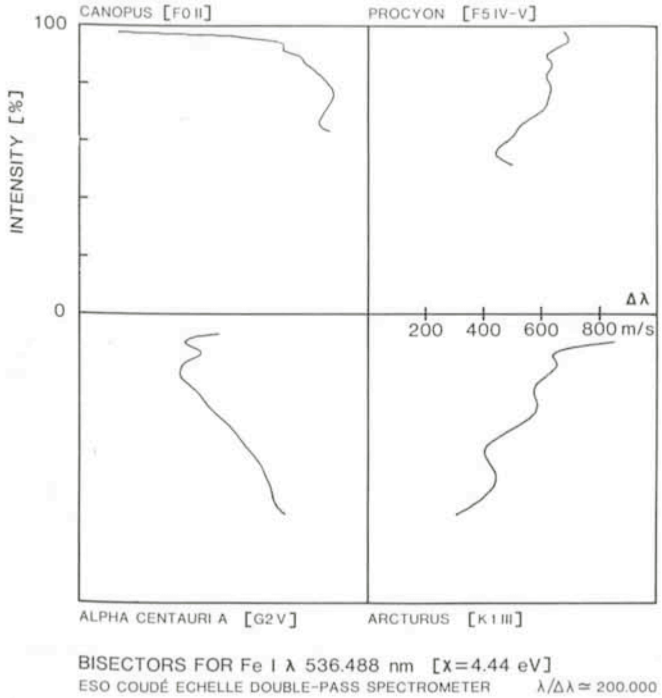

Fig. 5: *Considerable differences in surface convection patterns among different stars are here suggested by typical bisectors for four different spectral types. The small-scale undulations on the bisectors are due to noise, but their general slopes and curvatures are believed to be real. The bisector for the corresponding solar line is rather similar to that of α Cen A.*

Disks of a few stars with the largest angular diameters can be resolved already with current telescopes in the 4–6 meter range, while a fair number will become accessible to the planned very large telescopes. There are theoretical reasons to expect convection cells in giant stars to be much larger than those on the Sun: in fact, only a very small number of these might exist at any one time over the entire stellar surface. Optical phase interferometers currently under development promise to yield exciting data on such gross stellar structures.

Solar granules, however, have sizes around 1,000 km, only one thousandth of the solar diameter. Since a baseline of about 10 meters is required to resolve the disk of a nearby solar-type star, it will require a baseline a thousand times longer, i.e. 10 km, to resolve structures a thousand times smaller than a stellar diameter. The terrestrial operation of optical phase interferometers over such very long baselines would be coupled with formidable practical problems, caused by phase fluctuations in the Earth's atmosphere. However, an intensity interferometer (Hanbury Brown 1974), measuring not the interference between light waves, but rather the correlation between different telescopes of the quantum-mechanical intensity fluctuations in a source, is insensitive to phase, and can be operated regardless of a turbulent atmosphere. Intensity interferometry instead has various other limitations, including the circumstance that a faithful image of the source cannot be reconstructed in a simple manner. Rather the spatial power spectrum is obtained, i.e. information as to how contrasty the stellar surface is for different surface structure sizes.

As a spin-off from an ongoing development of a "quantum-optical spectrometer" at Lund Observatory, intended for studies of photon statistics with nanosecond resolution (Dravins 1982b), we are considering a possible modification of that instrument to be used for long-baseline intensity interferometry (Dravins 1981). In Fig. 6 potential baselines between telescopes around La Silla are marked. Of special interest is the 24 km baseline between the ESO 3.6 m telescope on La Silla and the 2.5 m Du Pont telescope of Carnegie Southern Observatory at Las Campanas. The line of sight goes across a valley at a considerable height above ground, promising small atmospheric extinction in horizontal optical paths.

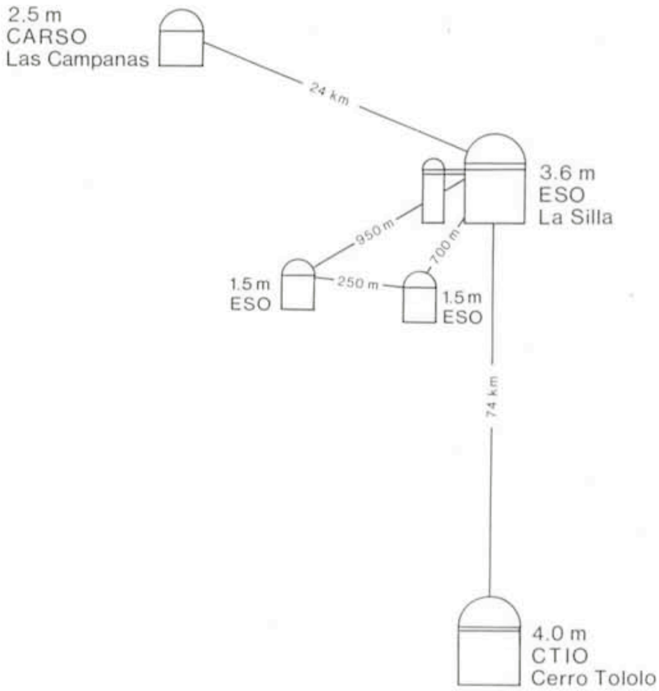

Fig. 6: *To directly observe the fine structure on stellar surfaces may ultimately require long-baseline optical interferometry. Inhomogeneities in the Earth's atmosphere in practice preclude phase interferometry over long baselines, but intensity interferometry does not suffer that limitation. In this sketch over telescopes on and around La Silla, potential baselines for future intensity interferometry are marked between telescopes that have free lines of sight between them. For example, the 24 km baseline between La Silla and Las Campanas offers an angular resolution of better than 10^{-5} arcseconds, adequate to detect structures the size of solar granulation on the surfaces of nearby stars.*

The concept would be to take light from one telescope (via a light fiber at the prime focus), collimate it and send it to a small receiving telescope at the other end, and then detect it there together with light from the other telescope. For the handling and processing of the signal, rather specialized units of digital electronics are required, and such are presently under construction. If these concepts ultimately prove workable, the resulting angular resolution would be measured in microarcseconds, and be equivalent to that of a 21 cm radio interferometer operating over a baseline of 10 million km! Such a spatial resolution, orders of magnitude superior to the highest so far achieved in astronomy, would be required to finally resolve structures of similar size as solar granulation on the surfaces of nearby stars.

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Distances to Planetary Nebulae

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When astronomers want to determine the properties of an object in the universe, they need a reliable distance to that object. Consequently there always has been much effort to find methods for distance determination. In the case of planetary nebulae, distances are very difficult to determine. Several methods have been tried but individual distances in general are still uncertain by a factor of two to three, sometimes even more. We have used an in principle powerful method, the "extinction method" to derive accurate distances for about 10 planetary nebulae.

The Importance of Accurate Distances

Planetary nebulae are believed to represent a late stage in the evolution of the many stars in the Galaxy with intermediate masses. During the planetary nebula phase, the star loses mass that becomes visible as a gaseous nebula which surrounds the central star.
Without an accurate distance to a planetary nebula important parameters such as nebular radius, nebular mass, luminosity and radius of the central star remain unknown. It is important to know the nebular mass, for example, because it determines the amount of gas that is returned to the interstellar medium by the planetary nebula phenomenon. This mass return has a large influence on the evolution of the entire Galaxy.

We also need accurate distances to many planetaries in order to determine their distribution in the Galaxy. This distribution can then be compared with distributions of other kinds of stars in order to try to determine which stars pass through the planetary nebula phase and which do not. Especially a comparison with the galactic distribution of white dwarfs and red giants is very interesting since it is believed that the planetary nebula phase lies between the red giant phase and the white dwarfs. Once the distance to a planetary nebula is known, the luminosity of the central star can be determined. The effective temperature of the central star can usually be derived so that the star can then be placed in a luminosity–temperature diagram. Many positions of central stars in such a diagram define in fact how temperature and luminosity evolve with time. This enables astronomers to check theoretical calculations of the evolution of stars with different masses.

Reasons Why Standard Methods Cannot be Applied

The reason that most planetary nebulae have unknown distances is that standard methods for distance determination are usually not applicable. All nebulae are much too far for distance measurements by means of trigonometric methods. With our knowledge about normal stars it is usually possible to determine their intrinsic luminosities by means of spectroscopy