Science with the VLT: High-Resolution Infrared Spectroscopy

G. WIEDEMANN, ESO

I. Introduction

Infrared astronomy has received an enormous boost ten years ago when the first small two-dimensional detectors became available. The 1987 Hilo conference on “Infrared Astronomy with Arrays” (Wynn-Williams & Becklin, 1987) marks the beginning triumph of IR arrays in astronomy. While ‘imaging observers’ greeted the new multi-pixel devices enthusiastically, their potential for spectroscopy was also immediately recognised. The VLT Working Group on Infrared Aspects (VLT Report No. 51, July 1986) had already emphasised the scientific potential of high-resolution (R ~ 10^5) spectroscopy in the 1–5 μm range and the large VLT-specific gain of this observational mode. The ESO VLT Instrumentation Plan, endorsed by the STC in March 1990, proposed the development of a dedicated high-resolution cryogenic echelle spectrometer or FTS and/or extending a ‘visible’ echelle spectrometer into the near-IR. Following the February 1992 ESO Workshop on High-Resolution Spectroscopy with the VLT, highest priority was given to a cryogenic echelle instrument at Nasmyth (rather than the combined focus previously considered) due to its large sensitivity gain relative to an FTS (Moorwood & Wiedemann, 1992; Ridgway & Hinkle, 1992), and the high scientific importance attached to the 2–5 μm region which cannot be competitively covered by an extended ‘visible’ spectrometer. Subsequently, a concept definition & preliminary design study for a cryogenic high-resolution IR echelle spectrograph (CRIRES) was prepared and presented to the STC Working Group “Scientific Priorities for the VLT” (ESO Scientific Report No. 15, December 1994). CRIRES has been ranked very high among the ‘future’ instruments in the VLT plan. High spectral resolution, coupled with the large wavelength coverage and the high sensitivity of a cooled echelle constitutes a unique observing capability, that cannot be substituted by other instrument combinations or observing strategies. Together with UVES, the VLT spectrograph for the optical and ultraviolet, CRIRES will open the possibility to obtain spectra with a resolution of R = 100,000 from the blue to 5 μm. The Scientific and Technical Committee (Resolution of 10 February 1995) recommended the continuation of the preliminary studies for CRIRES, in the context of clarifying possible instrument designs. The instrument concept has since been developed further with special consideration of technological advances in adaptive optics, IR detectors and optical components, and with regard to the evolution of scientific priorities of the VLT observatory.

Obviously, the demand for an extension of high-resolution spectroscopic capabilities at large telescopes into the IR (cf. ESO Workshop “High-Resolution Spectroscopy with the VLT”, 1992; UCLA/Lick/NOAO/McDonald Workshop “High-Resolution Spectroscopy with Very Large Telescopes”, Tucson, 1994) is being voiced increasingly at a time when technological improvements are indeed offering enhanced sensitivity and wavelength coverage of IR spectrometers.

This article summarises arguments for astronomical high-resolution spectroscopy in the infrared, illustrates some of the science priorities and provides a short description of the planned VLT instrument.

II. High-Resolution Spectroscopy in the Infrared

1. IR Source Brightness

‘Cool’ astronomical targets, whose study does not depend on particular visible or UV features, can be observed favourably in the infrared. In the era of photon detectors, the relevant Planck-function for the ‘brightness’, n_{ph} (photon flux in a velocity resolution element $\delta\lambda = \frac{\lambda}{R}$) of a blackbody at temperature T is:

$$n_{ph} = \frac{2c}{\lambda^3 \bullet R \bullet (\exp\frac{hc}{\lambda kT} - 1)} * A\Omega, \qquad [1]$$

where c is the speed of light, h and k are Planck’s and Boltzmann’s constants, respectively, and A Ω is the telescope étendue. Figure 1 illustrates the wavelength dependence of the photon flux for blackbody temperatures corresponding to stars of spectral type G2, K5 and M5. The second panel shows the resulting the λ-dependence of the photon flux ratios relative to 5000 Å. The IR-to-visible brightness ratio increases rapidly towards the cooler stars. The improvement over the 4000 Å range is even greater due to the exponential decrease of the stellar flux towards the blue. Monitoring K and M stars at 1.6 μm (H-band) or 2.3 μm (K-band) instead of the 5000 Å region, would have the equivalent effect of using a much larger telescope.

2. Use of Telescope Time

Telescope time is of similar value as telescope size, in particular to programmes targeting large samples, small effects or long-term variability. High-resolution observations of bright IR sources are largely unaffected by air-scattered sunlight and sky variability (OH emission or thermal background). The monitoring programme can therefore make extended use of twilight and morning time as much as permitted by telescope operations.

3. Obscured Sources

The IR brightness argument, of course, applies even more to sources that are obscured by dust at visible wavelengths: The ‘brightest’ extrasolar system object on the sky (IRC +10216) is invisible in the optical but has a 10 μm magnitude of –7! Star formation is observed predominantly in the IR, and the Galactic Centre can be studied only in the IR (Eckart & Genzel, 1996). Large visual extinction will make only the brightest LMC targets accessible to high-resolution VLT observations. Yet, none of the limiting distance moduli are severely compromised if IR spectroscopy is employed. High-resolution IR surveys in the Magellanic Clouds will be possible and M31 is well within reach (Sneden et al., 1995).

4. Infrared Spectral Diagnostics

The IR features an enormous number of spectral lines: The 1– 5 μm spectrum of a cool giant (Hinkle et al., 1995) contains roughly 6000 lines, of which about 1500 are of atomic and 4500 of molecular origin. Nearly half of these lines occur in the near-IR (λ ≤ 2.5 μm). Solar-type stars (T_{eff} < 6500 K), in particular, have rich line spectra from an abundance of molecules. Most rotation-vibration lines of light molecules occur in the IR. Einstein coefficients A_{ij} for spontaneous emission are typically. 1–100 sec^{-1} (A_{ij} ~10^8 sec^{-1} for atomic resonance lines). The lines are frequently formed near LTE, and probe predominantly cooler regimes (allowing molecule formation) that may not be accessible to the high-temperature optical diagnostics.

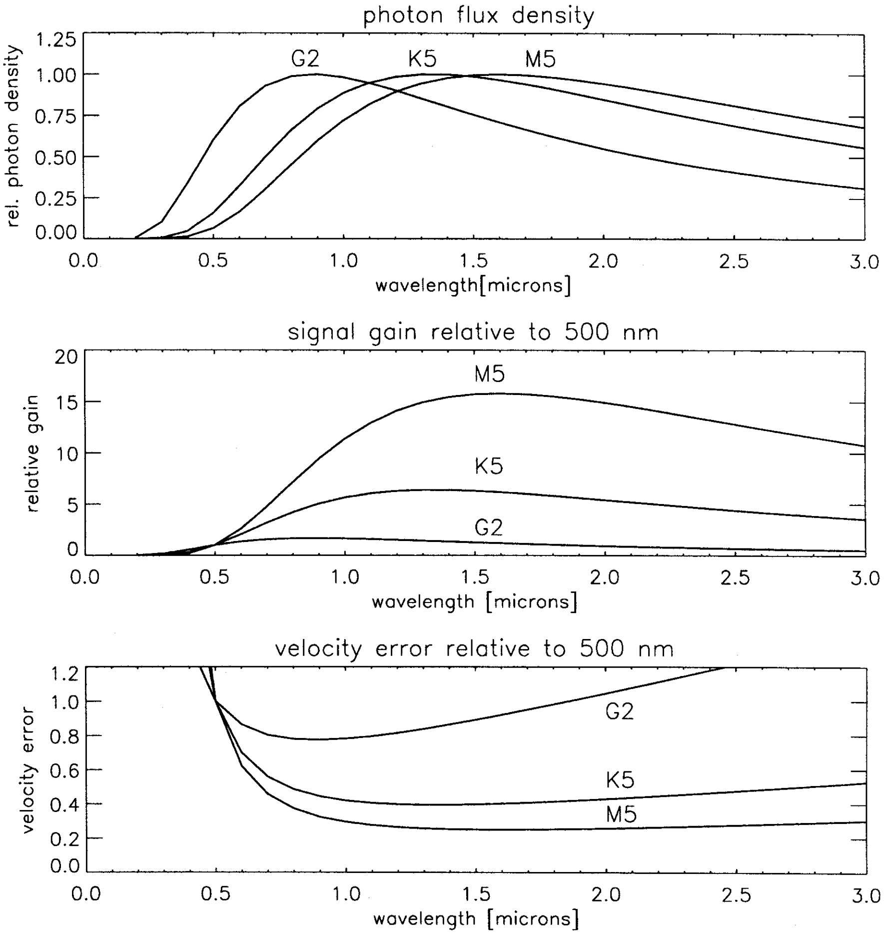

Figure 1: Upper panel: normalised photon flux density for blackbody temperatures corresponding to stellar spectral types G2, K5 and M5. Centre: wavelength-dependence of the photon flux, normalised to the flux at 500 nm for the three spectral types. The curves show the signal gain possible in the infrared for the cooler stars. The gain (vertical axis) is equivalent to an increase of the telescope area or a reduction of necessary integration times. Lower panel: wavelength-dependence of the corresponding velocity error, normalised to the error at λ = 500 nm on the same star.

The IR features a number of Zeeman-lines (1.56 μm Fe I, 2.23 μm Ti I, 12.32 μm Mg I). The ratio of σ and π-component splitting to the line widths for a given B-field increases linearly with λ and allows a more model-independent determination of field strengths in the IR (Saar, 1995).

The pure rotational (Δj = 2) quadrupole transitions in the vibrational ground state (v = 0) of molecular hydrogen, H_2, the most abundant constituent of the cool interstellar medium, occur in the infrared. Observable from the ground are several transitions at 3 μm – 5 μm, S(3) at 9.7 μm, S(2) at 12.28 μm and S(1) at 17.03 μm, the latter representing the lowest ortho-H_2 state, because of its statistical weight the most highly populated level in the coolest component of interstellar matter.

5. IR Spectroscopy: Why at a Very Large Telescope and at High Resolution?

IR spectroscopy fully exploits the collecting area ($\sim D^2$) gain of an 8-m over a smaller telescope, if the noise is independent of the telescope size. This holds for detector-limited faint-source observations in the near-IR, as well as for point-sources in the thermal IR, when the larger telescope's smaller diffraction limit and the use of an adaptive optics system keep the background étendue constant: $A\Omega \sim \lambda^2$. In the best possible case, the dominating noise source is the observed object itself, the S/N $\sim$ D is then solely due to the source photon statistics. This fundamental limit is familiar to optical observers; in the IR it is new for most targets. High-resolution spectroscopy, in particular, will benefit from the larger telescope size, as it is intrinsically handicapped by small signal levels.

Sensitivity gains greater than those due to the mirror size can result from instrument features, e.g. increased simultaneous spectral coverage or resolution. Usually these enhanced features are correlated with large instrument size, which could prohibit the implementation at low-emissivity foci of smaller telescopes.

In addition to the *information* contained in a high-resolution spectrum, there is a *sensitivity* increase for all unresolved spectral features through elimination of radiation not contributing to the signal (line photons) in both the source- and the background-limited cases. This gain associated with higher spectral resolution is equivalent to that of larger telescope size.

6. IR Spectroscopy: The Detector Array "Multiplex" Advantage

High-resolution (R $\approx$ 100,000) astronomical IR spectroscopy was dominated by the Fourier transform spectrometer (FTS) when 'noise' was primarily caused by poor detectors, and simultaneous wavelength coverage resulted in a net efficiency gain. This "multiplex" advantage was lost with improving detectors to broadband radiation-noise. Frequently, bandpass-limiting filters ($\Delta\lambda$) were required to reduce the radiation background on the detector, at the expense of spectral coverage. With cryogenic grating monochromators used for post-dispersion and ultra-low noise detectors it became possible (Jennings et al., 1986) to narrow the bandpass $\Delta\lambda/\lambda$ for FTS observations to a small fraction of a narrow filter band, with the additional advantage of easy tunability. A postdispersed FTS using a detector array to recover a larger spectral range has been proposed for the VLT (Maillard, 1992). The strongest boost for the IR echelle, however, came with the arrival of truly large two-dimensional detectors. (Early monopolising of the detector array market by optical imaging aficionados has given the world the *pic*ture *el*ement, "pixel". Attempts to introduce the spectroscopic analogue, "spexel" have not been successful). The evolution of astronomical IR spectrometers in the last decade was guided by the rapid increase in the size and the noise reduction of semiconductor detector arrays. The appeal of low-noise IR arrays to spectroscopy lies in the possibility to distribute all spectral elements onto individual detectors. This reduces the radiation - noise bandwidth to its absolute minimum, i.e. that of a spectral resolution element, $\delta\lambda$. The resulting noise improvement $\sim (\Delta\lambda/\delta\lambda)^{1/2}$ easily exceeds an order of magnitude. The spectral coverage ($\Delta\lambda$) corresponds to the available number of detector elements in an array. With the recent introduction of InSb and HgCdTe 1k $\times$ 1k arrays, an IR echelle at R = 10^5 can now offer a spectral coverage ($\Delta\lambda / \lambda \approx N_{det}$ / R) in a single order equal to that of an FTS with a noise-limiting filter system. Large detector arrays grant the multiplex gain to dispersive instruments. The FTS, although closer to the 'perfect' spectrometer than any other instrument type is being superseded by the more sensitive echelle spectrograph (Ridgway & Hinkle 1992) at the very large telescopes.

Figure 2 illustrates the signal levels from astronomical sources compared to noise levels prevailing in a high-resolution IR spectrometer. The fundamental

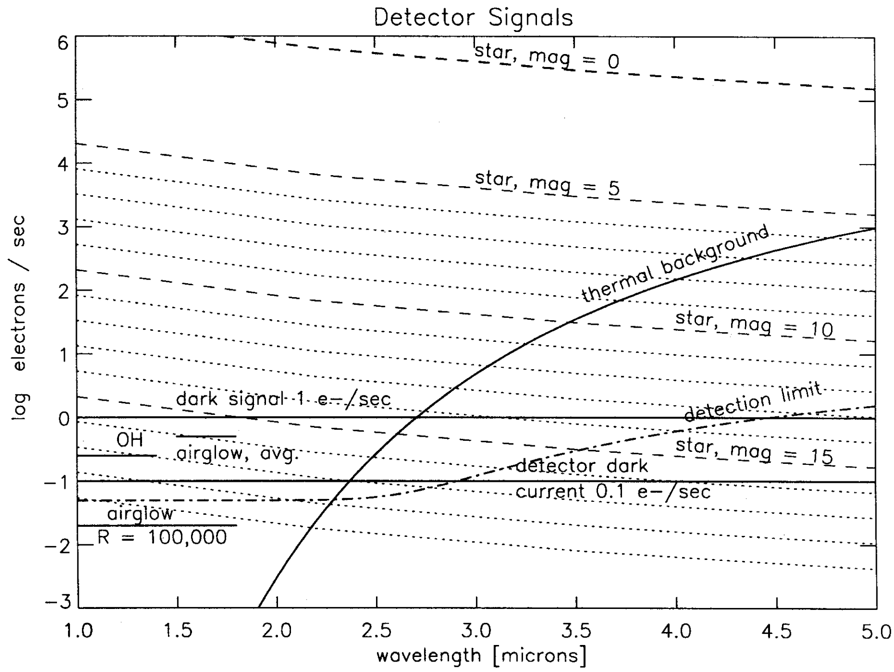

Figure 2: Detector signal levels (detected photons/sec) in comparison with the detector dark current (e^- /sec). Assumptions: Background temperature: 280 K, total emissivity 10%, total efficiency 10% (incl. atmosphere, telescope, detector Q.E.), R = 100,000, 0.1″/pixel, D_{Tel} = 8m, OH airglow values adopted from Maihara et al. (1993).

source-noise limit can be reached for many bright targets.

7. Exploiting the IR Advantage

Astronomy will benefit from IR echelle spectrographs in various ways. The VLT IR echelle will not only extend the number of observable objects considerably, but will offer capabilities not available otherwise. Sensitivity improvement can be aimed at fainter objects, higher spatial (extended sources), spectral and temporal resolution (or reduced integration times). Increased sensitivity will permit to extend studies from a few objects to a complete sample of an object class, access other, less luminous classes of objects, and to study previously unobservable phenomena in recognised but poorly-understood objects. Many extended sources have shown structure on small scales when observed with enhanced spatial resolution (e.g. auroral regions observed in H_3^+ on Jupiter). Studies of planets, stellar outflows, circumstellar disks, planetary nebulae, star-forming regions, etc. may benefit from the greater spatial resolution of the VLT echelle in the same way as, or – in combination with the spectral information – even more than pure imaging applications. The prospects for *solar-system* observations have been highlighted by Encrenaz (1994). The importance of high S/N, high-accuracy and high-resolution measurements on *bright* sources for astrophysics in general has recently been emphasised by several authors (Kurucz, 1992; Grevesse & Sauval, 1994; Dravins, 1994).

III. Science Priorities

1. Search for Extrasolar Planets: Infrared Radial Velocity Measurements

Recently, planetary companions have been identified to several solar-type stars, including a planet surprisingly close to 51Peg (cf. Mayor & Queloz, 1995). The hunt for extrasolar planets has concentrated on stellar reflex motions apparent in radial velocity (RV) variations, measured with optical high-resolution spectrographs (e.g. Hatzes, 1996). Until recently, the potential advantages of the IR could not be exploited because of a lack of instrumental sensitivity. Backed by the new technical capabilities, the IR now provides all qualities necessary for extrasolar planet searches:

• The extension of RV studies to the IR can constitute a quantitative improvement, equivalent to a substantial increase of the telescope collecting area.

• The extension of RV studies to the IR is essential, as complementary IR diagnostics may be needed to identify *stellar* causes of observed RV variations, which can be misinterpreted as reflex motions due to a planet.

The detection of extrasolar planets via RV measurements requires a precision in the range 1–10 m/sec. The reflex motion of the star increases linearly with the mass ($_*$ sin i) of the planet and with the inverse square root of its distance from the star. For instance, Jupiter's effect on the Sun amounts to ~12 m/sec, (that of the Earth only ~ 0.1 m/sec). The rms error σ of RV measurements:

$$\sigma = \frac{c}{R * \frac{S}{N} * N_L^{1/2}} \qquad [2]$$

improves with the signal-to-noise S/N in resolved stellar lines, the resolving power R, and the number N_L of lines in the stellar spectrum. Numerical simulations have demonstrated (Hatzes & Cochran, 1992) that a precision of 8 m/sec can be obtained with R = 100,000, S/N = 300 and N_L = 5. Actually achieved precisions in the optical have been reported (Hatzes, 1996) in the range 3–25 m/sec.

In order to assess possible quantitative infrared advantages of planetary RV searches, it is necessary to consider the wavelength dependence of the achievable S/N ratios and of spectral line densities. Candidate stars for planetary searches are considerably brighter than the background at all wavelengths. For a given line density, the velocity error σ therefore scales with the λ-dependence of the detected source flux according to eq. [1] and Figure 1. The lower panel in Figure 1 illustrates the resulting RV errors for each of these spectral types, relative to that achievable at 5000 Å on the same stars. Obviously, the IR can offer dramatic improvements for the cooler stars.

The search for extrasolar planets is a prime example for a monitoring programme that would benefit greatly from extended use of the VLT during twilight and possibly early morning time.

Infrared Lines for Radial Velocity Studies and Calibration

The IR spectra of late-type stars feature strong spectral lines suitable for radial-velocity studies (Fig. 3). Several 'windows' can be recorded simultaneously with a cross-dispersed IR echelle spectrograph. The use of CO Δv = 2 lines at 2.3 μm to monitor the apparent velocity of integrated sunlight and the use of IR N_2O lines as highly accurate velocity standards for RV measurement have been demonstrated and described by Deming et al. (1987,1994). CO, a well-studied molecule, can also be used for calibration in stellar studies, in particular if Doppler-shifted stellar CO lines are measured against their telluric (laboratory) counterparts.

The Importance of Complementary IR Diagnostics

Arguments for including the IR in planetary searches follow from two possible causes for periodic variations in the apparent velocity of integrated starlight, that could be mistaken for planets: magnetically affected vertical gas motions and stellar spots.

The radial velocity of integrated sunlight has been monitored by different groups using different spectral diagnostics. Deming et al. (1987, 1994) have determined RV variations with a peak-to-peak amplitude of 28 m/sec over a ~11 year period using as main diagnostic ($\Delta v = 2$) ro-vibration CO lines. The effect is very similar to that of Jupiter the Sun. McMillan et al. (1993), using a Fabry-Pérot in the optical, find an upper limit of 4 m/sec over the same period. The discrepancy is far greater than the respective errors. Viewed from far away, our Sun would thus appear to have an extra planet or not, depending on which spectral diagnostic is used. An explanation of the correlation with the solar cycle, (Dravins, 1982, 1985), is the inhibition of vertical motion of gases affected by magnetic fields. Monitoring of IR Zeeman lines might help to distinguish magnetic field changes from reflex motions as a cause of observed velocity variations.

A large dark spot on a rotating stellar surface can cause a periodic shift of a spectral line's apparent position through a reduced contribution to the disk-integrated flux at the velocity of the spot's geometric location. Conversely, one can exploit spectral diagnostics characteristic for and originating *in* the spot. These can be spectral lines of molecules that are stable only at the low temperatures prevailing in cool spots: sunspots observations, for instance, reveal an enormous number of characteristic spectral lines (Wallace & Livingston, 1992). Another diagnostic are Zeeman-sensitive lines whose components are spectrally split by the field of a cool magnetic spot (e.g. Hewagama et al., 1993). A spot is identified as a 'planetary pretender' if the Doppler variation of the IR spot signature is opposite in phase to that of the 'regular' stellar diagnostics.

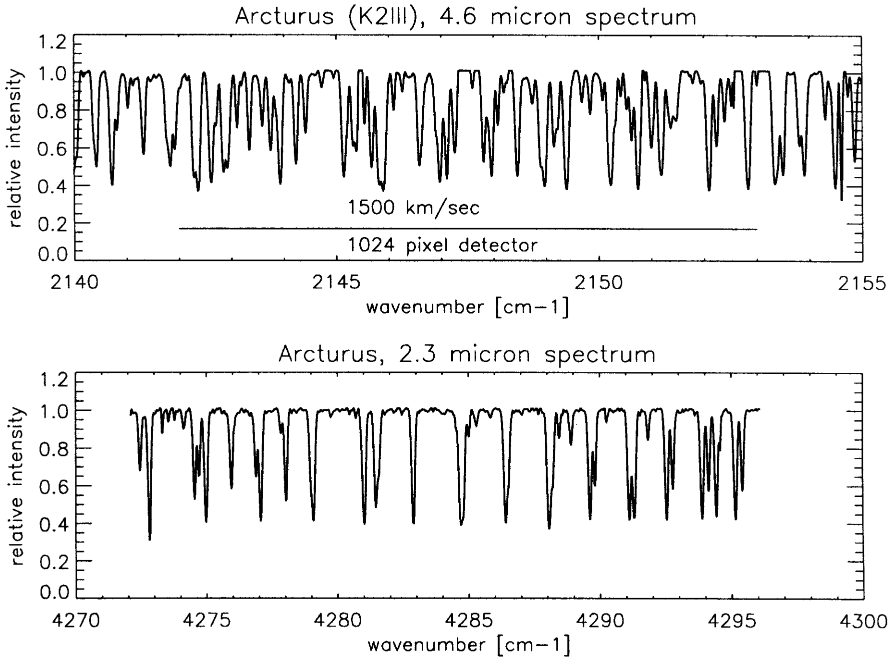

Fig 3. High-resolution (R >100000) spectra of αBoo (K2 III) from Hinkle et al (1995). The stellar spectra have been corrected for the atmospheric transmission. All absorption lines are of stellar origin and represent infrared transitions of carbon monoxide. Upper panel: fundamental (Δ v =1) lines in the M band; lower panel: first overtone (Δ v = 2) lines in the K-band. The horizontal bar indicates the range covered by a 1024 detector in a single order.

Fringe Benefits and other Applications of Planet-Search Techniques

The search for extrasolar planets automatically yields high-quality IR spectra of all stars included in a survey. Naturally, they can be exploited for a variety of scientific purposes. Spectra of candidate or other stars obtained with planetary search techniques, can examined for signatures of atmosphere dynamics or oscillations.

Planetary search tools can be applied to the suspected black hole in the Galactic Centre. Proper motions and velocity dispersion of the stars in the inner parsec of the galaxy have been measured to estimate the mass enclosed in the centre (Eckart & Genzel, 1996). The precise determination of the dynamic state and the mass/gravity distribution requires a measurement of the velocity *rate of change*. This is presently out of reach for proper motions, but in the range of RV techniques. Estimating the velocity variations of the inner late-type stars from the published centre distances and orbital periods yields numbers (10–100 m/sec/yr) similar to those achieved in RV planetary searches. RV studies in the Galactic Centre have to be conducted in the IR, as the stars are totally obscured at visible wavelengths.

2. Prospects for Direct Spectroscopic Detection of Extrasolar Planets

The direct detection of an extrasolar planet requires the identification of its host's reflected starlight or its own infrared radiation. Both signatures are faint and contribute minutely to the stellar flux; in favourable cases as that of the Jupiter-like companion 0.05 AU from 51Peg (Mayor & Queloz, 1995), the intensity relative to the stellar (m_V=5) 'background' is ~5 10^{-5} (Δ mag =11), if Jupiter's size and albedo are assumed. An $m_V \approx 16$ object is difficult to detect in close proximity to a star: on one hand the reason for the 'brightness' of a planet, proximity prevents, on the other hand, a separation of the observable *images.* Alternatively, the *velocity* separation between star and planet is easily within current observational capabilities, even for relatively distant planets, although close planets have a higher detection probability because of their greater reflected and thermal 'brightness'.

The orbital motion of an extrasolar planet periodically Doppler shifts its entire spectrum relative to that of its host star. This global frequency modulation uniquely distinguishes the planetary spectrum and can unambiguously identify its contribution to the total observed spectrum. The amplitude of this velocity modulation yields directly the mass ratio (or the mass if the reflex motion of the star has been established previously) according to $m_s v_s + m_p v_p = 0$. Intensity variations in the planetary signature 90 degrees out of phase with the velocity can be attributed to the illumination phases. Their amplitude can be directly related to the inclination angle of the orbital plane.

The frequency modulation of the planetary spectrum holds the key to the main problem of faint signal detection: the bright stellar 'background' must be suppressed extremely accurately to extract the planetary part from the observed combined spectrum. Background subtraction at the ~10^{-4} – 10^{-5} level, usually prohibitive in ground-based astronomy, is tractable in this special case: the modulation operates against the stellar wavelengths with an amplitude that is large compared to the (~few km/sec) line widths. (A simplified view is that of an isolated planetary spectral line moving "on and off" a position in the stellar spectrum). All foreign effects, not showing the same large velocity amplitude and periodicity over the entire spectrum can in principle be eliminated. The problem of accuracy is reduced to that of overcoming the statistical noise of the stellar flux. A reduction of that noise can be achieved if a spatially occulting mask is used at the spectrograph entrance to (partially) suppress the stellar flux. This is most efficient at the greatest projected separation of planet and star, i.e. when the planet has the largest velocity differential.

High spectral resolution is mandatory, as in all high-background applications, to maximise the signal (line photons)-to-noise (stellar photons in a resolution element), but the relative measurement does not ask for the high absolute velocity accuracy of stellar reflex motion studies. The arguments for investigating cooler stars preferably in the IR follow those for reflex motion studies.

Recent model calculations by Bjoraker et al. (1996) predict the possibility of strong methane line emission in the 3 μm ν_3 - band in a heated atmosphere as that of 51PegP. A direct planetary detection and the characterisation via CH_4 bands should be within the reach of CRIRES at the VLT.

Uncovering Planetary Pretenders

The search for velocity-modulated planetary signatures in stellar spectra can be hampered by time-variable, periodic or random *stellar* effects with power at the orbital frequencies. Variability can be due to: stochastic shock waves, magnetic field variations, spots on rotating surfaces, etc. Planetary detection is primarily concerned with the *magnitude* of these disturbing effects. Understanding the *cause* of observed variations can be the subject for interesting studies in the respective fields. It is nevertheless important for planetary searches, as it helps eliminating stars with large 'side effects' as potential targets.

Again, the IR can provide spectral diagnostics that are particularly well tuned to these 'parasitic' effects, such as Zeeman lines for magnetic fields or molecular LTE lines diagnosing the altitude dependence of stellar atmosphere dynamics.

3. Other Examples of IR studies

IR spectroscopy at an 8-m telescope can be applied to hot stars (non-LTE H-lines, atmospheric structure, disks, mass transfer), but offers even greater benefits in the study of stars of spectral type F5 and cooler (e.g. Grevesse & Sauval, 1994). Their IR spectrum contains lines from virtually all light diatomic molecules, including CNO in various combinations. The transition originate from a large number of excitation states and can therefore diagnose a wide range of physical conditions and processes. Two problems in stellar physics which will benefit from the VLT IR echelle are addressed below.

Stellar Magnetic Fields

The understanding of stellar evolution and dynamic processes in stellar interiors and atmospheres is closely tied to the understanding of the role of magnetic (B-) fields. The direct measurement of stellar B-fields is based on the Zeeman effect, which is characterised by a linearly increasing separation of σ- and π-components relative to the line widths with wavelength. Unambiguous, i.e. model-independent B-field measurements on stars require full separation of the Zeeman components and can only be performed in the IR. The first magnetic-field measurements on an M dwarf flare star, AD Leo, were reported by Saar and Linsky (1985), who recorded the Zeeman-split profiles of two titanium lines near 2.2 μm. A large fraction (73%) of the stellar surface is covered with an average field of 3800 G. Their FTS spectrum of AD Leo required a 6-hour integration to obtain a S/N of 25. Available instrumentation had been pushed to its limits to record one example of a magnetic-field measurement. An update on stellar magnetic-field measurements and a review of first achievements with IR echelle spectrographs has been given by Saar (1995).

The most powerful magnetic field indicators known today are the high-Rydberg MgI 12.32 μm lines. Since their discovery (Goldman et al., 1980), identification (Chang & Noyes, 1983) and interpretation (Carlsson et al., 1992), they have revolutionised solar magnetic field studies (cf. reviews at IAU Symposium 154). Few attempts have been made to search for these lines in stars, all with prototype visitor instruments at large telescopes (e.g. Jennings et al., 1986). Integrations of several hours merely detected the lines in very bright but magnetically inactive red giant stars (α Ori, α Tau). Dwarf and main sequence stars, the prime targets for magnetic field studies will only become accessible with IR echelles at large telescopes.

Stellar Atmospheres

The ro-vibration lines of CO at 2.3 and 4.6 μm originate at photospheric and chromospheric altitudes in spectral type F5 and cooler stars. Formed near LTE, the lines are relatively easy to interpret. Pioneering studies on the Sun (Ayres & Testerman, 1981), and Arcturus (Heasley et al., 1978), and subsequent investigation of a few bright stars by Wiedemann et al. (1994) have revealed a serious conflict between the stellar models derived from UV/visible observations and the IR molecular line observations, which led to the postulation of extended, molecular cooling-dominated surface areas in coexistence with the classical chromospheres. The confirmation of this 'thermal bifurcation' scenario (Ayres, 1981) would have profound implications for the standard models (e.g. Kelch et al., 1978), which depend strongly on the spatial averaging properties of the species from which they are derived (high-excitation lines on the Wien-side of the Planck-curve). Dust formation, suspected to begin at the stellar surface-interstellar medium interface could be affected through the altered grain-destroying UV radiation spectrum or the very low temperatures created by CO- and SiO cooling catastrophes (Cuntz & Muchmore, 1994).

Stellar Oscillations and Atmosphere Dynamics

The solar 5-minute oscillations can be observed in the CO IR transitions with great sensitivity due to the large number of lines formed over a wide altitude range (Ayres & Brault, 1990) and their close coupling to the local kinetic temperatures (LTE line formation). Different oscillation modes are triggered in the – directly unobservable – interior and the convective zone of late-type stars, from where they propagate to the visible surface. Extrapolating to stellar research, time resolved observations can probe processes in the *stellar interior* relating to evolution, age, etc. Measurement of correlated temporal variations in Doppler-shifts and line intensities probe the *dynamics* of cool star atmospheres. Such measurements, using CO ($\Delta v = 1$) and ($\Delta v = 2$) lines (Ayres & Brault, 1990) and 12.3 μm MgI lines (Deming et al. 1988) with large FTS have contributed substantially to the understanding of the solar photosphere/chromosphere region. Other stars are out of reach for current telescope/instrumentation, but will be accessible with a cryogenic echelle at the VLT. The study of acoustic shock waves in slowly rotating, i.e. magnetically inactive, stars (e.g. Cuntz et al., 1994) would contribute in a major way to the understanding of the elusive heating processes leading to the widely observed but poorly explained chromospheres in late-type stars (cf. *Mechanisms of Chromospheric & Coronal Heating*, eds. Ulmschneider, Priest & Rosner [Springer: 1991]). In this case, the sensitivity of the cryo-echelle permitting stellar observations is *fundamental*, since in the Sun – usually the primary case study for late-type stars – dissipation of magnetic (in addition to acoustic) energy accounts for substantial non-radiative energy input into the upper atmosphere and does not permit the identification of the individual causes of the observed structures. Again, few attempts to study oscillations of IR lines in cool stars with adequate time resolution have been undertaken in the past because of the lack of instrumental sensitivity.

IV. Observational Capabilities at the VLT

1. Instrument Concept

CRIRES is the IR echelle spectrograph in the revised VLT Instrumentation Plan. Its concept emphasises high resolving power ($R = 10^5$), high IR sensitivity and large spectral coverage. CRIRES is a cryogenic spectrometer utilising only reflective optics except for

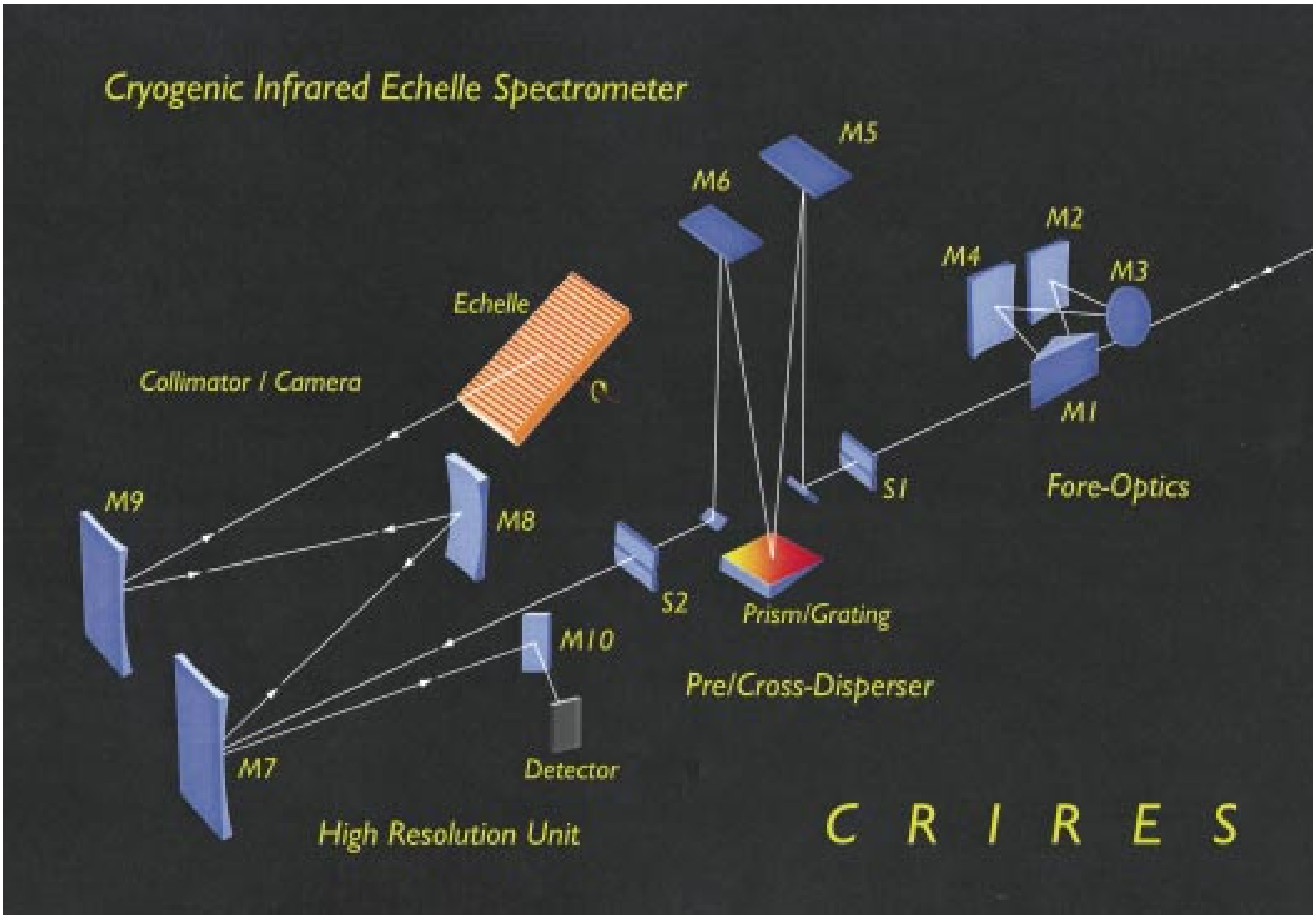

Figure 4: CRIRES, schematic of the optical layout.

the entrance window and the pre/cross-dispersing elements. The operating range extends from 1–5 μm. The non-thermal IR ($\lambda \leq 2$ μm) has been fully integrated in the concept as a range of immense scientific importance, containing spectral diagnostics such as the HeI 10830 Å line, CN bands in the J-band, CO Δv=3 lines and bandheads, and neutral metal lines in the H-band (1.6 μm).

The envisaged CRIRES would extend most of the UVES capabilities into the IR.

Due to the tight stability requirements, the Nasmyth platform with a low-emissivity focus is the natural location for the IR echelle spectrograph. The resolving power of 10^5 can be realised with a single 40-cm echelle, yielding a resolution-slit product of $R\Theta$ = 20,000 at an 8-m telescope. Observations of fainter point sources with a 0.2 arcsec slit require low-order adaptive correction for light concentration. A curvature-sensing AO system external to the instrument appears to yield the best overall performance. The increase of the background in the thermal IR would be only marginal, even irrelevant for bright-source observations. The reflection losses due to the extra optics are negligible compared to the reduction of slit losses.

The primary instrument mode will produce crossdispersed echelle spectra. A long-slit mode is envisaged, subject to optical field and mechanical constraints. The necessity for field-de-rotation will depend on the final slit length and its astronomical implications. No de-rotator is foreseen in the instrument. The task can be accomplished by the optical train of the AO system.

2. Instrument Description

The following description refers to the 3-D drawing (Figure 4). A more detailed description will be given in a forthcoming report. The instrument will be housed in a vacuum tank for operation at cryogenic temperatures. Optical system and radiation shields are cooled to 60–80 K. The detector operating temperature will be in the 20–30 K range. Functionally, the instrument can be divided into: adaptive optics unit, calibration unit, fore-optics, pre/crossdisperser and high-resolution section:

The calibration unit provides for flux calibration, detector flatfielding, and wavelength calibration of the echelle. It includes a gas cell for precision velocity measurements. The fore-optics section incorporates a cold pupil stop to eliminate all light not passing via the telescope secondary. A source image is formed at the entrance slit of the predisperser, which determines the spectral resolution of the echelle and acts as the main field stop. A small camera views the field image reflected off the predisperser entrance slit. Alternatively, the wavefront sensor for the AO system may be positioned here. This solution would eliminate the potential problem of uncompensated flexure between AO wavefront sensor and spectrograph slit.

The basic crossdispersed modes for all of the wavelength bands instrument will be realised by shallow gratings mounted interchangeably in the predisperser section. This concept retains the option for single-order observations with optimal parasitic light suppression, and the possibility to simultaneously record a low-resolution spectrum off the polished predisperser exit slit. An alternative design places the crossdisperser in the echelle section, as customary in optical spectrographs. This concept has not been proven for an IR spectrograph, however, and needs to be investigated further.

The beam expanding from the predisperser exit slit into the high-resolution section is collimated to illuminate the large echelle. Tilt-tuning of the echelle centres the desired wavelength on the detector. The dispersed light is returned through the 3-mirror collimator to the detector array(s). A small diverter mirror must probably be used to separate the spectrum from the entrance slit. The f/7 entrance and exit beam produces the required plate scale of 0.1 arcsec/pixel, with two detector elements sampling the nominal 0.2 arcsec entrance slit. A sampling finer than two pixels per resolution element can be obtained by scanning the grating in steps corresponding to fractions of a pixel.

3. Performance

Sensitivity and S/N

Figure 2 shows the contributions to the detector signal which determine the noise and the detection limits given in Table 1. A useful definition of 'sensitivity' must refer to the different conditions under which observations are carried out. Faint-source limiting magnitudes, largely determined by instrument properties are given in Table 1. Signal-to-noise ratios, relevant for small effects in bright' (Table 2) sources, are listed in Table 3.

With a read-noise expected in the 10 e^- range, the faint limits are dictated by the dark current (< 1 e^- /sec/px) in the J, H (outside of strong OH airglow lines) and K bands and by the thermal background radiation (telescope and atmosphere) at the longer wavelengths. The S/N increases as the square root of the integration time. In the faint source limit, the S/N increases linearly with the signal.

Table 2 shows the stellar magnitudes at which the flux from the source begins to dominate the noise. The S/N increases as the square root of the signal in the fundamental bright source limit. To illustrate the system efficiency, Table 3 lists the integration times required to achieve a S/N of 100 on a 5th and a 10th magnitude star at all wavelengths.

TABLE 1: Limiting magnitudes for S/N = 3 in 1 hour.

λ (μm)	1.2	1.6	2.2	3.3	4.2	4.7
mag	18	17.5	17	15	13.5	12.5

Assumptions: Dark signal (incl. detector current, stray light) 1 e^-/sec, total emissivity .1, total efficiency 10% (incl. atmospheric and telescope transmission, instrument efficiency, detector Q.E.), accumulation of > 100 e^- per exposure to overcome read noise.

TABLE 2: Stellar magnitudes where point source observations become source-noise limited.

λ (μm)	1.2	1.6	2.2	3.3	4.2	4.7
mag	16	15	14	10	7	5

TABLE 3: Integration times required for S/N = 100 on a 5th and a 10th mag star.

λ (μm)	1.2	1.6	2.2	3.3	4.2	4.7
T[sec], mag = 5	<1	1	2	2	3	5
T[sec], mag = 10	50	100	160	350	6,000	15,000

V. Conclusion

"We trust that in the final vote, committees and directors will favour high resolution, because even though most astronomers don't use it, they know as we know that astrophysics comes out of high-resolution observations" (S. Ridgway, Conclusion of an invited review talk at the ESO Workshop 'High-Resolution Spectroscopy with the VLT' 1992)**.**

References

Ayres, T.R. 1981, *Ap.J.* **244**, 1064.
Ayres, T.R. & Testerman, L. 1981, *Ap.J.* **245**, 1124.
Ayres, T.R. & Brault, J. 1990, *Ap.J.* **363**, 705.
Bjoraker, G & Deming, D. 1996, private communication.
Carlsson, M. , Ruttren, R.J. & Shchukina, N.G. 1992, *A&A* **253**, 567.
Chang, E. S. & Noyes, R.W. 1983 *Ap.J.* **275**, L11.
Cuntz, M. & Muchmore, D.O. 1994 *Ap.J.* **433**, 303.
Cuntz, M., Rammacher, W. & Ulmschneider, P. 1994, *ApJ.* **432**,690.
Deming, L.D. & Plymate, C. 1994 *Ap.J.* **426**, 382.
Deming et al 1987, *ApJ.* **316**,771.
Deming, L. D. , Boyle R.J. , Jennings, D.E. & Wiedemann G. 1988, *Ap.J.* **333**, 978.
Dravins, 1982 ARA&A 20,61 and 1985, IAU Coll. 88, Stellar Radial Velocities.
Dravins, D. 1994, in The impact of long-term monitoring on variable star research, (eds. de Groot & Sterken), Kluwer Acad. Publishers.
Eckart, A. & Genzel, R. 1996, *Nature*, Vol. **383**, 415.
Encrenaz, T., 1994, *The Messenger*, No. **75**, 12.
Goldman, A. et al. 1980 , *New Atlas of IR Solar Spectra* Vol. **2**, Dept. of Physics, Univ. of Denver.
Grevesse, N. & Sauval, A.J. 1994 in *Molecular opacities in the stellar environment*, (ed. U.G. Jørgensen), IAU Coll. 146,
Hatzes, A. 1996, Report to ESO Working Group on Extrasolar Planets.
Hatzes, A.P. & Cochran, W.D. 1992, in Proceedings of ESO Workshop on High Resolution Spectroscopy with the VLT (ed. M.-H. Ulrich).
Heasley, J.N., Ridgway, S.T., Carbon, D.F., Milkey, R.W. & Hall, D.N.B. 1978, *Ap.J.* **219**,970.
Hewagama, T., L.D. Deming, D.E. Jennings, V. Osherovich, G. Wiedemann, D. Zipoy, D.L. Mickey, & H. Garcia 1993, *Ap.J.* Suppl, **86**.
Hinkle, K.H , Wallace L. & Livingston, W. 1995, *Arcturus Atlas*, Astron. Soc. of the Pacific, San Francisco.
Jennings, D.E., Deming, L. D., Wiedemann, G. & Keady, J. J., 1986, *ApJ.* **310**, L39.
Kelch, W.L., Linsky, J.L., Basri, G.S., Chiu, H. , Chang, S., Maran, S.P. & Furenlid, I. 1978, *Ap.J.* **220**, 962.
Kurucz, R.L. 1992, *Rev. Mexicana Astron. Astrof.* **23**, 187.
McMillan et al 1993, *ApJ.* **403**, 801.
Maihara, T., Iwamuro, F., Hall, D.N.B., Cowie, L.L., Tokunaga, A.T. & Pickles, A.J. SPIE, 1993, Vol. **1946**, 581.
Maillard, J.-P. 1992 in Proceedings of ESO Workshop on High Resolution Spectroscopy with the VLT (ed. M.-H. Ulrich).
Mayor, M & Queloz, D. 1995, *Nature*, Vol. **378**, 23.
Moorwood, A.F.M. & Wiedemann, G. 1992, in Proceedings of ESO Workshop on High Resolution Spectroscopy with the VLT (ed. M.-H. Ulrich).
Ridgway, S. & Hinkle, K 1992, in Proceedings of ESO Workshop on High Resolution Spectroscopy with the VLT (ed. M.-H. Ulrich).
Saar, S.H. & Linsky, J.L. 1985 *Ap.J.* **299**, L47.
Saar, S. 1995, in Stellar Surface Structure, IAU Symp. 176.
Sneden, C. et al 1995, *PASP* **107**,997.
Wallace L. & Livingston, W. 1992, *An Atlas of a Dark Sunspot Umbral Spectrum from 1.16 to 5.1 μm*, KPNO/NSO Technical Report.
Wiedemann, G., Ayres, T.R. , Saar S.H. & Jennings, D.E. 1994 *Ap.J.* 423.
Wynn-Williams C.G. & Becklin, E.E. 1987 (eds.) Infrared Astronomy with Arrays, eds., Univ. of Hawaii, Hilo.

Günter Wiedemann
e-mail: gwiedema@eso.org