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From Planets to the Big Bang with High-Resolution Spectroscopy at the VLT

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Introduction

Some years ago, M. Harwit showed that most cosmic discoveries were connected with the occurrence of a significant technical step or the opening of a new window on the Universe. Without question, high-resolution spectroscopy associated with very large collecting area will be such a major tool to attack vital astrophysical problems. Beside serendipitous discoveries, there are several areas of research to be investigated with a high-resolution VLT spectrographic capability. The VLT should not miss the opportunity to venture into an almost virgin universe and make discoveries.

Here, we are talking about resolving power R of at least $1-1.5\times10^5$, simply because many important pending problems cannot be tackled with lower resolution. Many of these are reviewed in the proceedings of the ESO Workshop on "High Resolution Spectroscopy with the VLT" held in Garching in 1992. We will briefly give here only a few exciting examples of potential achievements in various fields through high-resolution absorption spectroscopy at the VLT.

Technical Advances

Measurements of equivalent widths of interstellar lines (IS) are indeed quite independent of the resolution. However, it is well known that they can yield very large errors on column densities when multiple components are present on the line of sight and when lines are saturated (on the flat part of the curve of growth). The former situation appears very general, even for the short lines of sight of the solar neighbourhood. The latter one is less common, at least for part of the IS lines in the visible spectrum. But both cases will become severe limitations when probing the diffuse IS medium beyond what is currently reachable in the galactic plane with the available telescopes.

Sufficient resolution is required to resolve the velocity structure of the lines of sight. This is the only way to gain information on individual clouds, on average separated by a few km/s, that is now badly needed instead of integrated properties. Amongst physical parameters, temperature is directly accessible only through the intrinsic width of the lines. For purely thermal broadening, the width increases with decreasing mass of the studied ions, and the lightest element having an observable resonance line in the visible is lithium (the lighter elements hydrogen, deuterium and helium show up in the currently unaccessible far UV, except Lyα observable with the Hubble Space Telescope but which is always heavily saturated and blended). Nevertheless, even through the Li I doublet, IS gas at 1000 K gives a full width at half maximum of 2.57 km/s, requiring already $R > 1.2-10^5$. Higher resolution is mandatory in order to derive true b-values from cooler IS gas, even though careful profile fitting analysis of several lines may help to artificially increase the resolution by a factor of perhaps 2 or so depending on the signal-to-noise ratio. Moreover, using lines of different ions in the same velocity components will allow to also determine any turbulent velocity, another important and poorly known parameter for the dynamics of the interstellar medium.

Astrophysical Considerations: Interstellar Medium

The Li^7 equivalent width for IS diffuse clouds such as those in front of ζOph or ϱ Oph in which typical temperature is very likely below 100 K, is of the order of the mÅ, claiming thus for S/N ratios well above 100. Because both stars are bright enough, these two lines of sight are well studied with the ESO CES at La Silla, which has provided $R=10^5$ for more than ten years. The CES is usually fed by a 1.4-m telescope. The jump to an 8-m-class one will so much increase the number of potential targets that many stars more deeply embedded in cloud cores will become accessible, allowing thus to link the properties of the diffuse clouds currently studied in absorption to those of the denser and colder regions detected in the IR or mm radio range.

A more specific programme would be the measurements of the IS abundances of light elements, in particular beryllium and lithium which are only observable in the visible range around 3130 Å and 6707 Å respectively. The knowledge of their present-day abundances, and even more uniquely of the ratios Be/Li and Li^7/Li^6, is a key-milestone to severely constrain cosmological scenarios and galactic chemical evolution models. This kind of observations needs extremely high S/N ratios. For instance, IS Li^6 has been recently detected for the first time towards ϱ Oph (Lemoine et al., 1993), thanks to a S/N ratio ≥ 2700 per pixel, implying a limiting detectable equivalent width of 0.043 mÅ (3 σ). The resulting Li^7/Li^6 ratio $\sim$ 12.5 is in strikingly good agreement with the meteoritic value which is thought to be representative of the early solar system, and cannot as yet be explained by the most recent and elaborated evolutionary models. This has been achieved after 13 hours of integration time with the CES linked to the ESO 3.6-m telescope via fiber optics, on a $m_v \sim 5.0$ star. The same measurement is going to be published for ζ Oph ($m_v=2.7$) with a S/N ratio above $\sim$ 7000! (see Figures 1 and 2). However, this is restricted to the 4–5 stars on the whole sky which are bright enough but still shining through a dense cloud to enhance the expected column density. It should be done in many individual clouds in order to statistically establish the significance of the first results and to directly test the cosmic ray production of Li; the gain from one VLT unit should even allow to see possible variations in the supernova rate through IS clouds in other galactic spiral arms.

Measurements in the visible range of molecules like CH, CH^+, CO^+ or C^2 are also of prime importance for interstellar chemistry; they can also yield the carbon isotopic ratio C^{12}/C^{13} and the dark clouds temperature (see e.g. Black and Van Dishoek, 1988; Crane et al., 1991; Hobbs, 1973, Vladilo et al., 1993). In fact, requiring very high spectral resolution and S/N ratios, all these abundance studies need to be performed towards more and more distant targets, in very different environments or where galactic gradients become sensitive, or in other spiral arms. In several hours of integration time with the VLT, the most abundant of these species might be detectable in the Magellanic Clouds, which would give access to less processed extragalactic material, to be compared to the more extreme metallicity towards the galactic centre. Equivalent widths of several tens of mÅ in neutral IS sodium at 5890 Å, good tracer of H I, are already gathered at $R=10^5$ towards the very brightest Magellanic supergiants with the 3.6-m telescope, but Ca II at 3930 Å, providing information on ionization, is just barely feasible at that resolution (Molaro et al. and Vladilo et al., 1993). The use of an 8-m telescope would allow a much more complete mapping of the Clouds, yielding in particular the still poorly known depth structure of the Clouds.

Astrophysical Considerations: Extragalactic

Another example of the need for resolution in the 10^5 range at the VLT is the study of the narrow absorption lines in quasar spectra. Just to give two exciting cases, one can first mention the measurement of the cosmic background radiation temperature, T_{CBR}, at high redshifts. Besides black body microwave observations, IS lines from the lowest rotational levels of the CN molecule around 3875 Å have been used for many years to derive the precise CBR temperature at the present epoch (e.g. Palazzi et al., 1992). However, this is the only point determined up to now. According to the Big Bang theory, T_{CBR} depends in a simple way upon the redshift, and its determination at different z would really be a new extremely strong observational argument in favour of the Big Bang. A convenient radiometer for directly measuring the background radiation at earlier epochs would be neutral carbon. The ground state of C I splits into three levels separated by energies of the same order as kT_{CBR} at $z > 0.5$, when C I lines show up in the visible range. At such epochs, contrary to the galactic ISM where collisions are much more efficient, C I should be appreciably excited by the CBR. Up to now, because of the lack of resolution available even for the brightest QSOs to resolve the C I line splitting, only an upper limit of 16 K at z=1.776 has been assigned by Meyer et al. (1986). Such measurements in several QSOs' absorption systems at different z are waiting for the VLT.

The second case is the measurement of the deuterium abundance in adequate absorption components of the so-called Lyα forest in quasar spectra. Only directly observable in the far UV, the present-day IS value of the D/H ratio is still controversial since variations might exist in the very local ISM (see e.g. Ferlet, 1992). New determinations are under way with HST, but restricted to very short lines of sight. Furthermore, to go from the IS value to the primordial one – which is of major cosmological significance since it is highly sensitive to the universal baryon density and thus can constrain the density parameter – requires very uncertain evolutionary models. While early models suggested a relatively low astration of deuterium (a factor 2–3), the accumulation of obser-

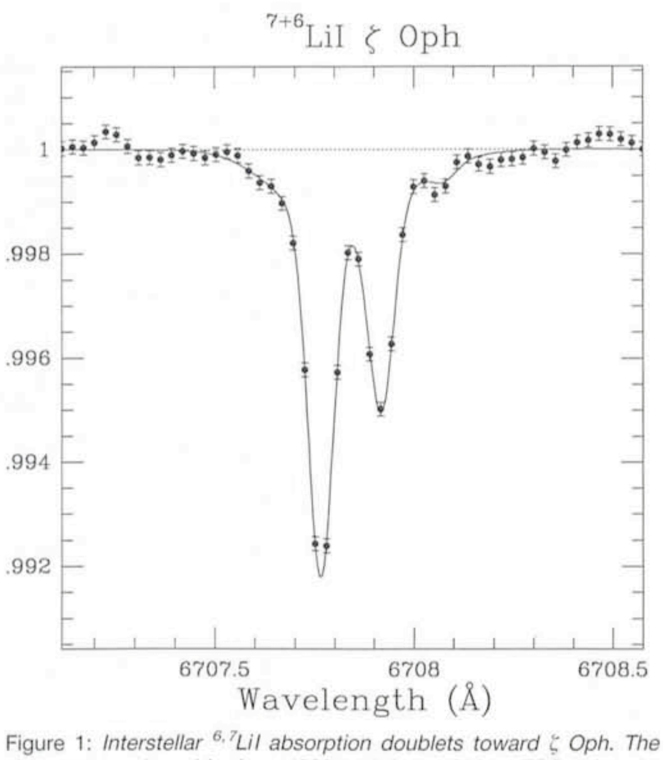

Figure 1: *Interstellar ^{6,7}Li I absorption doublets toward ζ Oph. The data were gathered in June 1990 and June 1992 at ESO using the CES linked to the 3.6-m telescope via a fiber link. The total integration time is 15h., the resolution is $\lambda/\Delta\lambda = 100{,}000$, and the signal-to-noise ratio 7500 per pixel, or 11 per resolution element, giving a 3 σ limiting detectable equivalent width of 18 μÅ!*
The solid line represents the fit to the data with two interstellar absorbing clouds on the line of sight, and taking ^{6}Li and ^{7}Li absorptions into account. Ordinates are arbitrary units; error bars are 1 σ.

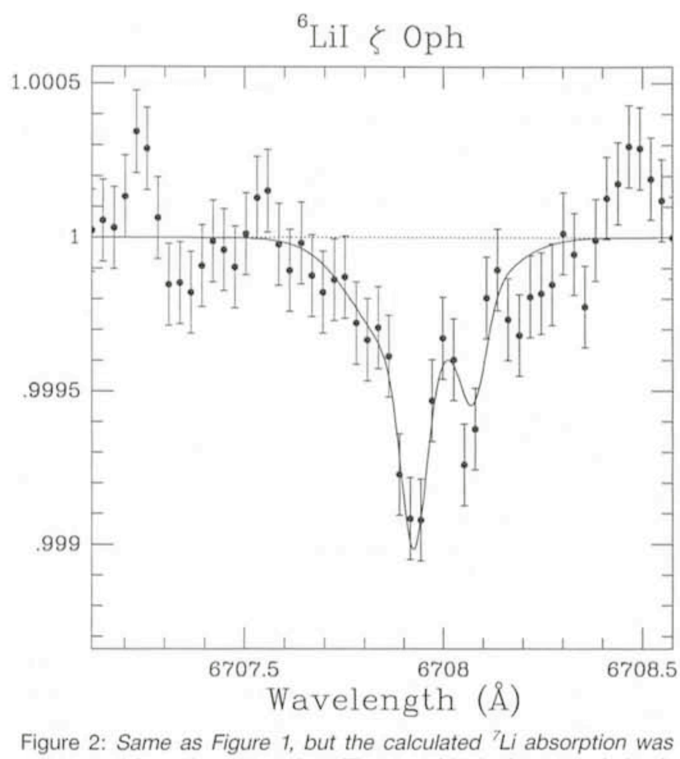

Figure 2: *Same as Figure 1, but the calculated ^{7}Li absorption was subtracted from the data points. These residuals thus reveal clearly the ^{6}Li absorption doublet. The depth of this doublet is less than 0.1 % of the continuum (see ordinates). The solid line represents the previously calculated ^{6}Li fit to this profile. Error bars are 1 σ.*

vational data made apparent that factors of 10–50 are needed if the standard Big Bang nucleosynthesis predictions are to remain consistent with the observations (see e.g. Audouze, 1987). The idea is therefore to evaluate D/H in media as primordial as possible, and in absorption systems having a wide range in abundances to be able to discriminate between theoretical models of galactic chemical evolution.

The feasibility of such measurements has been last explored by Webb et al. (1991), assuming existing possibilities: 10 km/s resolution, 10 hours integration time with a 4-m telescope on a $m_v \sim 17.5$ QSO (i.e. S/N = 15), and the first 5 Lyman lines are observed, implying $z_{abs} \geq 2.6$. Deuterium appears detectable only as an extension in some of the Lyman line wings, but the D I line is not resolved and D/H very difficult to measure, although some particular ranges of values for the crucial velocity dispersion b and for the H I column density may increase the chances of making cosmologically significant measurements. Obviously, the VLT will make these D/H analysis not only easier but also, as for the T_{CBR} determination, more numerous: Webb et al. (1991) identify about 35 suitable absorption systems with high enough N_{HI} in the around 30 known QSOs with $z \geq 2.6$ and $m_v \leq 17.5$; about 10 times more potential QSOs as yet undiscovered are expected with these characteristics. It will thus be possible to perform a more extensive statistical investigation in order to place tight constraints on chemical evolution models and the Big Bang itself.

Astrophysical Considerations: Planetary Systems

The study of protoplanetary systems is another field of research we would like to mention here. The β Pictoris disk is the prototype of this new area which will surely become more and more important in the near future with the discovery of other systems. As for the previous fields, this asks for high spectral resolution at high S/N ratios, but also for high temporal resolution. In the case of β Pic, the very large UV and visual circumstellar absorption data base is presently interpreted as the signature of cometary-like bodies evaporating when grazing and falling onto the star, perhaps through perturbations of a huge small bodies reservoir by an already formed planet orbiting β Pic. Such events last few hours and have to be spectroscopically followed in velocity and equivalent width simultaneously in different lines (like the Ca II doublet), or as close as possible in time (see e.g. Lagrange-Henri et al., 1992).

The search for extra-solar giant planets through extremely precise radial velocity measurements is also now entering the discovery phase, since a ± 5 m/s sensitivity has been reached for very bright stars by two techniques: Fabry-Perot and gas absorption cell. It has been vigorously put forward as part of the first stage of the recently announced TOPS Program of NASA: Toward Other Planetary Systems. For instance, Jupiter induces an amplitude variation of 13 m/s in the radial velocity of the Sun over a period of 11.9 years. The limits for such long-term follow-up of very many stars are more imposed by the apparent brightness of the observed stars. This is why TOPS is intended to be performed in partnership with the Keck Observatory.

Astrophysical Considerations: Stars

Last, in the field of stellar research, one can briefly mention the study of non radial pulsation in early-type stars. For cooler stars, again the determination of the Li isotopic ratio, the measurements of surface magnetic fields from the Zeeman broadening, the separation of different broadening mechanisms such as rotation and macroturbulence in G and K stars, time-resolved spectroscopy (on time scales as low as ~1 sec) of flares, the mapping of stellar surface features (spots) through Doppler imaging techniques, and an approach to astroseismology, etc. This kind of problems, that we have limited to those really needing spectral resolution in the 10^5 range and/or time resolution, are currently tackled at ESO; but the small aperture of the available telescopes simply prevents most interesting targets to be reached, e.g. M dwarfs, T-Tauri stars, stars in clusters, Pop II stars, etc. A new potentially also very interesting case is the study of the remnants of the AGB winds during the post-AGB stellar evolutionary phase towards planetary nebulae. Here again, all the targets are very obscured and optically very faint.

Conclusion

It is obvious that the jump from 4-m to 8-m (and *a fortiori* from 2-m) class telescopes will very much increase the number of observable targets so that entirely new results will undoubtedly come up. The type of scientific questions we have discussed here are only tractable with a spectral resolution VLT mode in the $1-2 \times 10^5$ range. It does not at all mean that an ultra-high resolution mode ($R \geq 3 \times 10^5$) would be useless; an enormous amount of information on physical processes is waiting for that mode, some examples having been pointed out in e.g. Ferlet (1993) and Dravins (1993). It has to be noted also that for both modes, a small spectral range, say few tens of Å to record simultaneously both lines of the Ca II doublet, is often sufficient. It would be advisable to implement these modes at the VLT coudé focus, in order to provide enough room and stability, and avoid the field rotation of the Nasmyth focus. This will moreover leave open the future possibility to dedicate a 4-m class "Auxiliary" telescope for high-resolution spectroscopy.

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