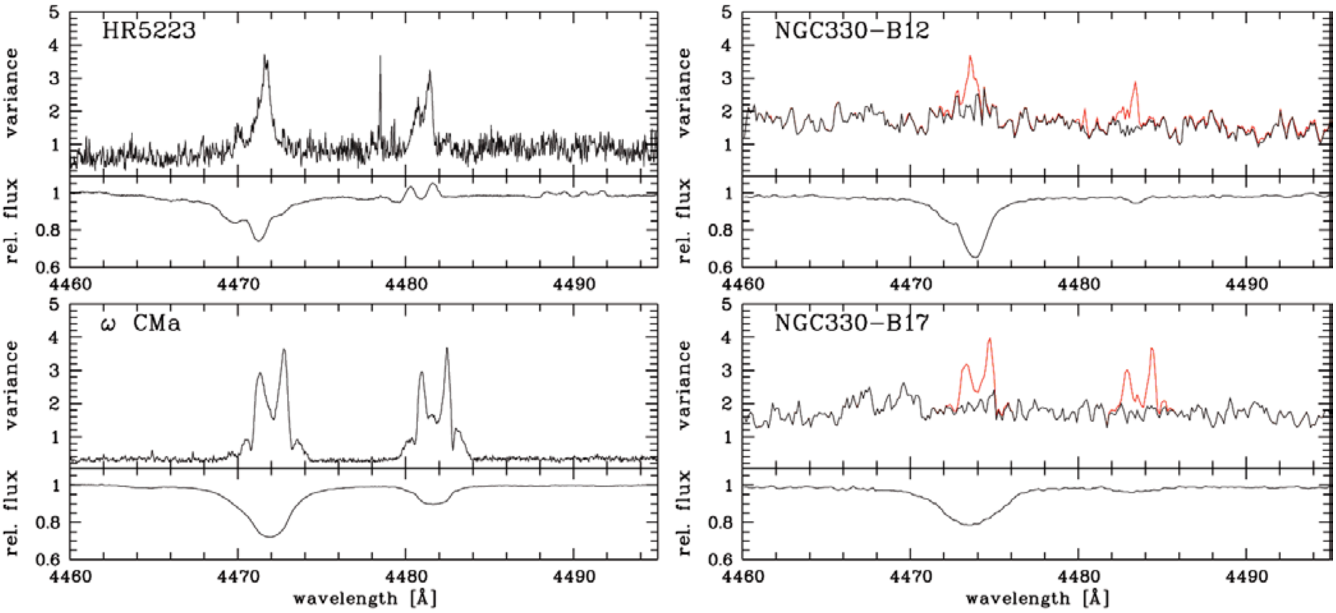

Figure 7: Mean line profiles and their temporal RMS variance of Galactic (left; observed from La Silla) and SMC (right; observed with the VLT and UVES) early-type, pole-on Be stars compared. The red overplot demonstrates the expected RMS variance if the SMC stars underwent the same variability as their Galactic counterparts. The differences in the strength of the Mg II 4481 line are due to the metallicity of the SMC, which is about 80% lower than in the Galaxy.

on Kueyen in August 2001, and the Director General's Discretionary Time Committee recommended some reconnaissance observations.

The results are shown in Figure 7: Not only is there a difference between Galactic and the two SMC Be stars we observed but the latter are not variable at all at a level that would have been easily detected in Galactic observations of the same quality! There is, of course, the possibility of this result being due to small number statistics. However, since we believe that this possibility is probably very small, we submitted a letter to some major astronomical journal. Only to be told by the first referee that our data were not interesting. This problem has meanwhile been fixed. But the puzzle of the Be phenomenon persists with some old questions answered and some new complexities added, and the expansion and analysis of the HEROS database continue.

Acknowledgements: We are indebted to too numerous people at the Landessternwarte Heidelberg and the European Southern Observatory (La Silla and Garching) to give credit to all of them individually. We have not forgotten the manifold technical, scientific, and administrative support.

Spectroscopy of Quasar Host Galaxies at the VLT: Stellar Populations and Dynamics Down to the Central Kiloparsec

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1. Scientific Context

Discovered more than 40 years ago, and in spite of tremendous theoretical and observational efforts, quasars and their host galaxies remain puzzling objects. It seems now established that at least all large galaxies harbour massive black holes (e.g., Magorrian et al. 1998), and that quasar-like activity may be a common but transient phenomenon in galaxy evolution. However, very little of the physical processes at work *during* such episodes of nuclear activity is actually understood. The following questions list some of the important issues still to be solved: What are the time-scales involved in the fuelling (or refuelling) of massive black holes? Does the material they burn come from mergers? Do all galaxies contain a black hole or only the most massive ones? What is the exact relation between galaxies and quasars? Is the feedback from a luminous Active Galactic Nuclei (AGN) onto its host galaxy important? Is it in the form of huge quantities of ionising radiation or does it manifest itself directly as mechanical outflows such as jets?

Quasar host galaxies have been studied almost exclusively by imaging. Examples of such work are numerous and use a broad variety of telescopes, instruments and post-processing techniques. The Hubble Space Telescope (HST) data of Bahcall et al. (1997) have shown that quasars occur in all types of galaxies. Stockton et al. (1998) used adaptive optics near-IR data to map the plumes and jets around the quasar PG 1700+518. Recent HST optical studies have established that high-luminosity quasars generally reside in big ellipticals, irrespective of radio properties (McLure et al. 1999, McLeod & Rieke 1995a, Disney et al. 1995). There also seems to be a trend that more luminous QSOs are hosted by more massive galaxies (McLeod & Rieke 1995b).

A more detailed and quantitative understanding of the physical conditions in hosts galaxies can only be obtained from spectroscopic observations. The data available in this field are very scarce, and although extensive quasar host spectroscopy was conducted already in the early 1980s (e.g., Boroson et al. 1985), they have never really been followed up with improved instrumentation and analysis techniques, except for a few isolated objects (among them 3C 48 being the probably best-studied case in this field – e.g., Chatzichristou et al. 1999, Canalizo & Stockton 2000. See also Crawford & Vanderriest 2000 for similar work with other objects).

Nearly all spectroscopic observations up to now were designed as long-slit, “off-nuclear” spectroscopy. Off-nuclear observations attempt to minimise contamination by the bright quasar, by placing the slit of the spectrograph a few arcsec away from it. While this surely contributes to minimise contamination by the quasar, it also minimises the signal from the host galaxy itself! In addition, only the outer parts of the host are probed, hence giving a biased idea of the overall stellar content, and loosing the dynamical information.

Recent developments in instrumentation and the advent of sophisticated post-processing techniques have made it possible to tackle in a new way the problem of light contamination by the central AGN. We describe in the present article the first results of a comprehensive VLT spectroscopic campaign which, at variance with the traditional approach, is designed as “on-axis” spectroscopy combined with spectra deconvolution. The case of the low-redshift quasar HE 1503+0228, at z = 0.135 is taken as an example and placed in a broader context which will involve optical and near-IR two-dimensional spectroscopy with instruments such as GIRAFFE, SINFONI and FALCON.

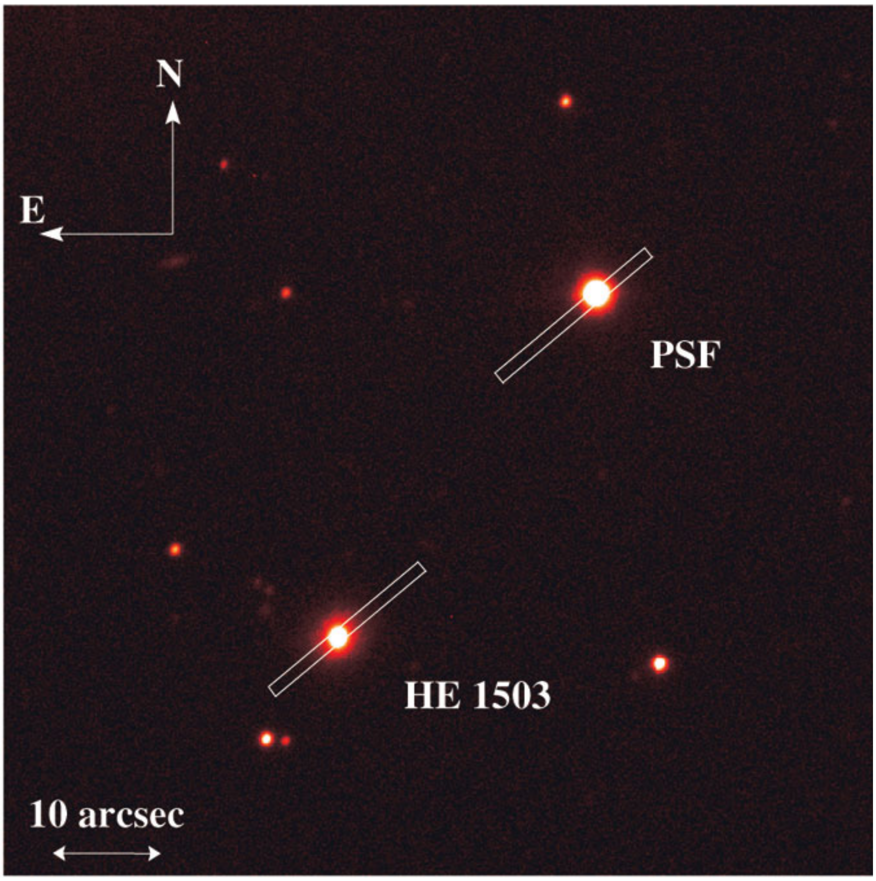


Figure 1: Part of the VLT/FORS1 pointing image. The seeing is 0.62″ on this 30-sec R-band exposure. The 1″ slits used to obtain the spectra of the target and of the PSF star are indicated.

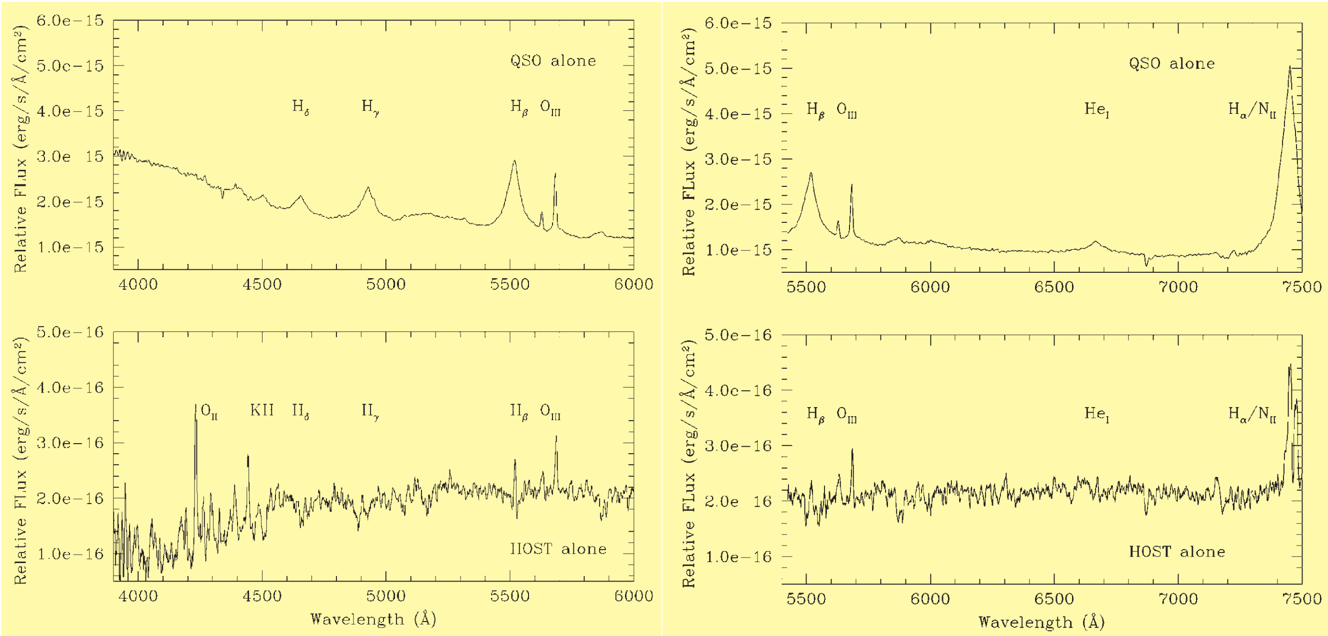
2. VLT Spectroscopic Observations

Our goal is to study the stellar and gas contents of quasar host galaxies as well as their dynamics, and to compare their properties with “normal” galaxies without quasar activity. This not only requires deep spectra with moderately high spectral resolution, but also accurate decomposition of the data into the individual spectra of the quasar and of its host galaxy. We have chosen to carry out our study for optically bright radio-quiet quasars selected from the Hamburg/ESO survey (Wisotzki et al. 2000). Our sample involves quasars with $M_B < -24$ and $z < 0.33$, for most of which we also have sharp H-band imaging obtained at the NTT with SOFI. The spectroscopic work in progress is based on the VLT/FORS1 observations of 18 of these objects, with ANTU at Paranal observatory. The 5 observing nights allocated in the context of the programmes 65.P-0361(A) and 66.B-0139(A) were all clear and with seeing often below 0.6 arcsec.

Decomposition of the quasar and host spectra requires knowledge of the instrumental Point Spread Function (PSF). We have therefore chosen the MOS mode of FORS1 in order to observe simultaneously the quasars and PSF stars in the field of view. One 19 arcsec long slit was placed on the quasar, several other slits were placed on PSF stars (note that there was always at least one PSF available), and the rest was used to observe galaxies in the immediate environment of the quasar. We show in Figure 1 part of the FORS1 field of view around HE 1503+0228, where are indicated the positions of two slits used for the quasar and for the only bright PSF star available in this field of view. Each object was observed with the three high-resolution grisms of FORS1 and the standard collimator (0.2 arcsec pixel), giving a mean spectral resolution of 700. The exposure time was 1200 seconds in each of the three grisms, in grey time.

3. Spectra Decomposition and Stellar Population

The method used for decontaminating the host’s spectrum from the quasar light is an adaptation of the MCS image deconvolution algorithm (Magain et al. 1998) to spectroscopy (Courbin et al. 2000a). It uses the *spatial* information contained in the spectrum of one or several PSF stars in order to *spatially deconvolve* the science spectrum. This results in higher spatial resolution across the slit and in a spectrum which is decomposed into several channels. One of these channels contains the spectrum of extended objects, while there is one individual channel for each point source in the slit. In the application we already showed for the gravitational lens HE 1104-1805 (Courbin et al. 2000b and Lidman et al. 2001), there were two channels for each of the quasar images and the channel for the extended sources was used for the



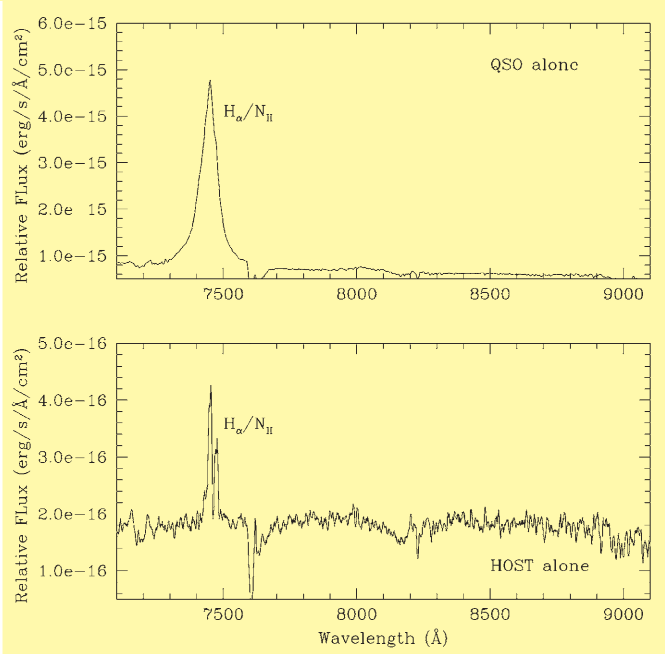


Figure 2: One-dimensional deconvolved spectrum of HE 1503+0228, at z = 0.13552, and its host galaxy. Each panel corresponds to one FORS1 grism and displays the individual flux-calibrated spectrum of the quasar and its host galaxy. Note that the spectrum of the host shows no trace of the AGN broad emission lines. These lines are seen narrow in the spectrum of the host. Note also the very good agreement in the deconvolution of the 3 grisms in the overlapping regions. The spatial resolution on the deconvolved 2D spectra is 0.4 arcsec.

lensing galaxy. For quasar hosts, there is one channel for the quasar and one for the host galaxy.

Figure 2 displays the integrated spectrum of HE 1503+0228. Each panel shows the deconvolved/decomposed data for the three FORS1 grisms. The quality of the decomposition can be judged from the many narrow emissions seen in the host and hidden in the quasar spectrum. In addition, there is no trace of residuals of the quasar broad emission lines in the spectrum of the much fainter host. Courbin et al. (1999) already showed from simulations that such a decomposition was possible, but there were no suitable MOS data at that time to test the method on real spectra.

Luckily, almost all regions of astrophysical interest in the spectrum of HE 1503+0228 are observed in two different grisms. This allows for double check of the deconvolution results and to build a composite spectrum from 4000 Å to 9500 Å, with higher signal-to-noise ratio in the regions where the grisms overlap. Note in Figure 2 the excellent agreement between the deconvolution done for each grism, in the regions of overlap. The data are plotted here as they come from the deconvolution process, without any adjustment to ensure a good match between the different grisms. Accurate spectrophotometry can actually be done on the deconvolved data.

The host galaxy spectrum we present here has a signal-to-noise that varies between 10 and 25 per Å from the bluest parts to the reddest. This allows the analysis of the stellar population. Measuring the emission and absorption lines in the spectrum of HE 1503+0228, and comparing them with that of normal spiral and elliptical galaxies (Kennicutt, 1992a, b, Tragger et al. 1998), we find that the spectrum of the HE 1503+0228 host is that of a normal early-type spiral galaxy. Its interstellar medium is ionised by star formation and only a tiny residual excitation can be attributed to the central AGN.

4. Dynamics of the Host

Many of the quasar hosts we observed (about 30–40%) display prominent narrow emission lines that sometimes extend over several arcseconds. These lines, and the fact that we observe with the slit centred on the quasar, allow us to derive the rotation curve of the host, from the outer parts of the galaxy, down to the central kiloparsec.

In the deconvolution process described above, the difference in spatial properties between AGN (point source) and the host galaxy (extended component) is used to separate the spectra of these two sources. A smoothing in the spatial direction is applied for this purpose to the extended component. However, such a method is not optimal for deriving velocity curves, as spatial smoothing (which is not precisely known as it varies with the local S/N) may modify the spectral position of the lines at a given spatial position, by averaging spatial components of different radial velocities. We have therefore designed another method, for extracting narrow emission lines in two dimensions, from the rest of the spectrum. The method decomposes the data in: (1) the narrow emission lines of the host, and (2) the low-frequency signal composed of the spectrum of the quasar plus the *continuum* of the host galaxy. The result of the process is shown in Figure 3, where the rotation of the galaxy is conspicuous.

The extracted emission lines are used to compute the rotation curve of the galaxy in HE 1503+0228 as shown in Figure 4. The first data point (green dots) is at only 0.5 kpc away from the AGN (assuming H_0 = 65 km s^{-1} Mpc^{-1}, Λ = 0, and Ω_M = 0.3). In order to infer the mass of the galaxy, and of its central regions, we use a three-component model including a central mass concentration, a thin disk, and a spherically symmetric halo of dark matter. Fitting this model to the data gives the blue line in Figure 4, which has to be corrected for the inclination of the galaxy and other geometrical effects (red curve). This inclination is estimated from our SOFI and FORS images. We find $i \sim 46 \pm 9°$. This is certainly the major source of uncertainty on the mass of the galaxy. A preliminary estimate of the mass we can infer for the host of HE 1503+0228 is $(1.3^{+0.4}_{-0.1})$ 10^{10} $M_\odot$ within 1 kpc. The total mass of the galaxy, by integrating our mass models over the 10 kpc is $(1.4^{+0.5}_{-0.2})$ 10^{11} $M_\odot$, or about the mass of a "normal" spiral galaxy.

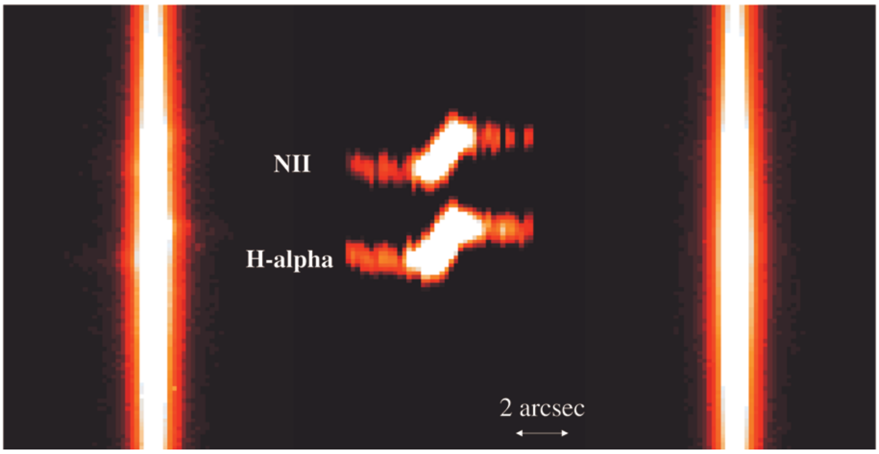


Figure 3: Example of emission lines extraction for the Hα and N II lines in the I grism. The original data are shown on the left. The middle panel shows the emission lines of the host galaxy alone, whereas the right part shows the sum of the quasar spectrum and of the continuum of the host galaxy.

5. Towards 2D Spectroscopy and High Spatial Resolution: GIRAFFE, SINFONI and FALCON

The study of quasar host galaxies is a fantastic application for high spatial resolution capabilities. We show from a very simple and short FORS/MOS observation that a distant quasar host galaxy can already be probed in spectroscopy down to the central kiloparsec, making it possible to infer in a quantitative way the mass of the galaxy and to compare its stellar population with other non-AGN galaxies.

Our observation was taken under average seeing at Paranal, about 0.6–0.7″ depending on the grism. A gain of a factor 10, as is obtained with adaptive optics, will allow for similar studies easily up to redshift 1 or slightly more. This means that we will be able to follow the evolution with time of the interactions between AGNs and their hosts. It also means that the nearest AGNs will be resolved into great detail, maybe down to the central parsec, where the dust torus and the outer parts of AGN accretion disks become visible (e.g., Marco & Alloin, 2000, Alloin et al. 2001).

Modern observatories, and in particular ESO, offer a broad range of instruments not only capable of high-resolution imaging at NGST-like resolution, but also capable of producing two-dimensional spectra at such a spatial resolution. GIRAFFE is a step towards high-resolution 2D spectroscopy, and will already allow us to map the whole velocity field (gas and stars) of low-redshift quasar-host galaxies. Stellar population gradients might be seen across the objects, and accurate mass determination will become possible by allowing for accurate determination of the inclination of the galaxy. At low redshift, GIRAFFE observations are simple. A 1-hour shot will already reveal the velocity field of the gas. Adding two hours to this will allow to follow the important Calcium absorption lines, hence the stellar velocity field.

From our FORS observations, we can safely predict that GIRAFFE will efficiently be used up to redshift 0.5, for an average seeing observation at Paranal. SINFONI is similar to GIRAFFE, but its adaptive optics system and its near-IR detector will allow to follow quasar hosts at much higher redshifts (up to z = 2), especially since laser guide stars will allow to access the entire sky or close to this, with the AO instruments.

On a longer term, FALCON, a near-IR integral field spectrograph using multi-conjugate adaptive optics, shall take place at the VLT. With its many Integral Field Units (IFU) and a local adaptive optics system (i.e., around each IFU) the instrument will be used to observe *simultaneously* quasars, PSF stars (for accurate post-processing techniques) and galaxies in the immediate vicinity of the quasar. The FALCON concept (Hammer et al. 2002) not only allows to map the velocity field of the quasar host, but also the one of each component of the groups or clusters of galaxies involved in the fuelling process of the central AGN.

The study of quasar host galaxies is therefore one more of the numerous areas that will highly benefit from high angular resolution now made possible in a systematic way on large telescopes, either by using AO or by applying post-processing techniques, or a combination of both.

Acknowledgements

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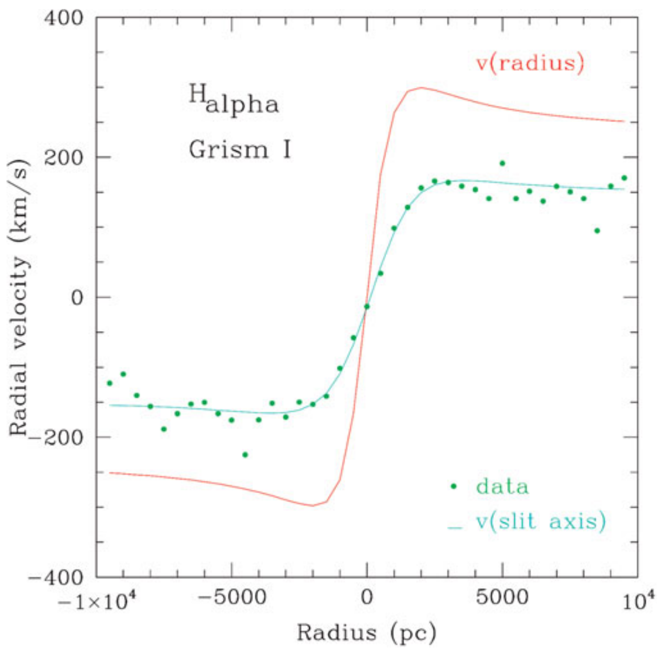
Figure 4: Rotation curve of the host galaxy of HE 1503+0228. The dots are the data points obtained using simultaneously the Hα and N II lines in the I-band grism. The blue curve is the fit of our three component galaxy model, and the red curve shows the fit after correction for the inclination of the galaxy and of a number of slit and seeing effects (see Courbin et al. 2002 for more details).



particular Claire Moutou, Merieme Chadid, Emmanuel Jehin, Herman Boehnhardt and Ricardo Scarpa. Géraldine Letawe is a teaching assistant supported by the University of Liège, Belgium. Frédéric Courbin acknowledges financial support through Chilean grant FONDECYT/3990024 and from the European Southern Observatory. Marie Curie grant MCFI-2001-00242 is also gratefully acknowledged.

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The Crab Pulsar and its Environment

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V. FLYCKT (ESO, Luleå University of Technology)

1. Introduction

The Crab Nebula is a supernova remnant. The supernova exploded in 1054 AD, and was monitored by contemporary Chinese astronomers (see e.g., Sollerman, Kozma, & Lundqvist 2001). Today the nebula offers a spectacular view, with a tangled web of line-emitting filaments confining an amorphous part ghostly shining in synchrotron light. The beauty of the Crab makes it repeatedly appear in PR pictures, even from a southern observatory like the VLT (Fig. 1).

Figure 1: The VLT (UT2 + FORS2) view of the Crab nebula. A composite of images in B(blue), R and S II(red), taken in November 1999 as part of commissioning. ESO PR photo 40f.

At the heart of the nebula resides the energetic 33-ms Crab pulsar. This $m_V \sim 16$ object actually powers the whole visible nebula. The Crab nebula and its pulsar are among the most studied objects in the sky. This astrophysical laboratory still holds many secrets about how supernovae explode and about how pulsars radiate and energise their surrounding nebulae.

A main theme for pulsar research has been to understand the emission mechanism for the non-thermal pulsar radiation. This is still to be accomplished. No comprehensive model exists that can explain all the observed features of the radiation. Observationally, only recently was a broad range UV-optical spectrum of the pulsar published (Sollerman et al. 2000). We have now extended the study into the infrared (IR).

But even if most of the research on the Crab pulsar has concerned the radiation mechanism, almost all of the spin-down energy actually comes out in the particle wind. This is the power source of the Crab nebula. The stunning image of the pulsar environment obtained with CHANDRA (Fig. 2) captures a glimpse of the energetic processes at work. Direct evidence of the pulsar activity has long been seen in the system of moving synchrotron wisps close to the pulsar itself.