Real-Time Spectroscopy of Gravitational Microlensing Events – Probing the Evolution of the Galactic Bulge

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1. Introduction

Gravitational microlensing refers to the apparent brightening of a background source by a lensing object located sufficiently close to the line of sight. This gravitational focusing effect does not require the intervening object to be luminous, and hence has been suggested as a way to detect astrophysical dark matter candidates in the Galactic halo [1]. The challenges in detecting this effect are two-fold: Firstly, the probability of a star in nearby galaxies (including our own) to be microlensed is tiny, only one in a million. This means that millions of stars have to be monitored, and automatic data-processing is essential. Secondly, one has to tell microlensing events apart from many other intrinsic variations exhibited by stars. Fortunately, the symmetric, achromatic and non-repeating nature of a microlensing event distinguishes itself. Indeed, both obstacles have been overcome and the detection of microlensing has become a full enterprise [2]. Many groups are currently monitoring the Galactic bulge and the Large and Small Magellanic Clouds for microlensing events*. At the time of writing, more than two hundred microlensing candidates have been discovered by the DUO, EROS, MACHO, and OGLE collaborations; of these, about fifteen are towards the LMC, one towards the SMC, while the rest are towards the Galactic bulge [3, 4, 5, 6, 7]. An exciting observational advance is that most microlensing events can be identified in real-time while they are still being lensed. This allows detailed follow-up observations with much denser sampling, both photometrically and spectroscopically. Two groups, the PLANET and GMAN are conducting detailed photometric follow-ups [8, 9]. Our group is engaged in spectroscopic observations of selected microlensing targets (see section 2).

ESO has played a leading role in the spectroscopic studies of microlensing events. The first spectroscopic confirmation of microlensing was performed at ESO by Benetti, Pasquini and West [10], while the first spectral observations of a binary lens event were carried out by Lennon *et al.* [11]. Such spectroscopic studies are not only the strongest discriminator between variable stars and genuine microlensing candidates but also of importance for many other reasons. The spectra obtained allow detailed analysis of source properties, such as atmospheric parameters, stellar radius and radial velocity. Accurate stellar radii are essential to derive relative transverse velocities, a quantity much needed in order to derive the lens masses. Spectroscopic studies also yield essential information for a small fraction of more peculiar events. For the exotic binary caustic events [12], spectroscopic studies can resolve the stellar surface with very high accuracy and provide new opportunities to study limb-darkening profiles, well known only for the Sun. Spectral analysis can also provide important clues to some puzzles in microlensing. For example, there appears to be an over-abundance of long duration events. Currently, it is not even known whether these lensed sources belong to the disk or bulge populations. As these populations are thought to be kinematically and chemically distinct, a spectroscopic survey is needed to disentangle the disk and bulge contributions.

While these aspects are of importance for understanding the observed microlensing rate towards the Bulge, Lennon *et al.* [11] demonstrated for the

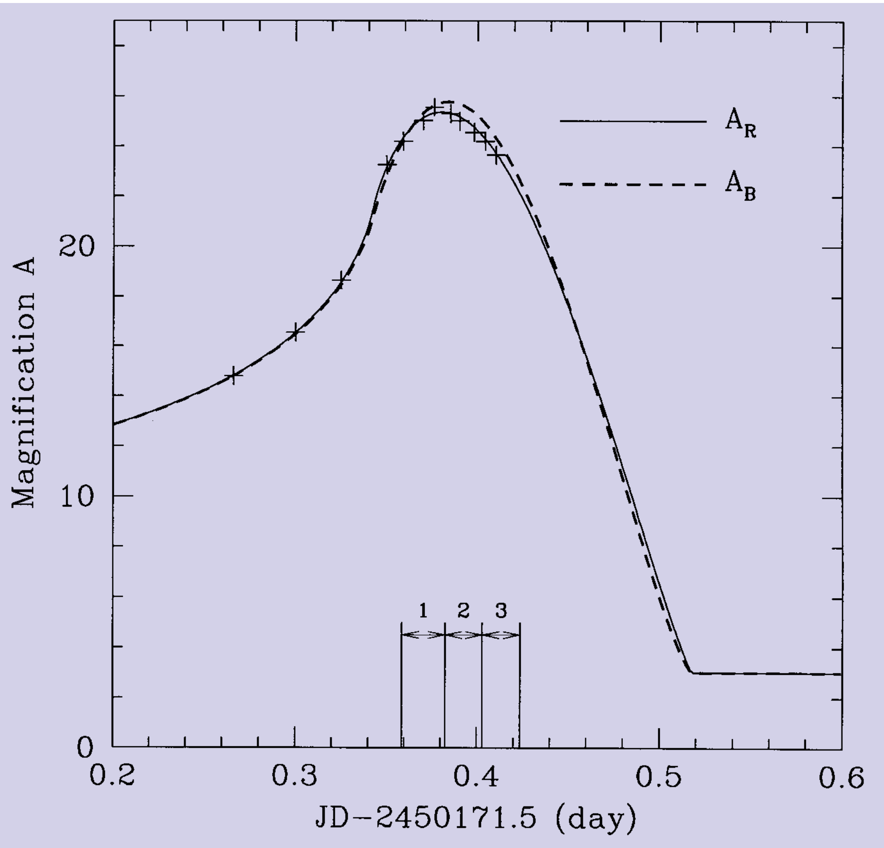

Figure 1: Simulation of the R-band light curve for the microlensing event 96-BLG-3 near the caustic crossing (solid line) and approximate data points (crosses). The thick dashed line shows the prediction for the B-band. The difference between the magnifications in B and R is due to the variation of limb-darkening profiles with wavelength (here assumed to be like the Sun). The vertical lines at bottom indicate the three-minute time intervals during which our spectra were taken. The binary nature of the lens was announced on March 28 (JD=2450171) by the MACHO collaboration [13], approximately one day from the peak. An earlier caustic crossing on March 25 was also identified, as well as previous complex behaviour.

*More information can be found at http://wwwmacho.anu.edu.au/ for the MACHO collaboration. Links to other collaborations can also be found there.

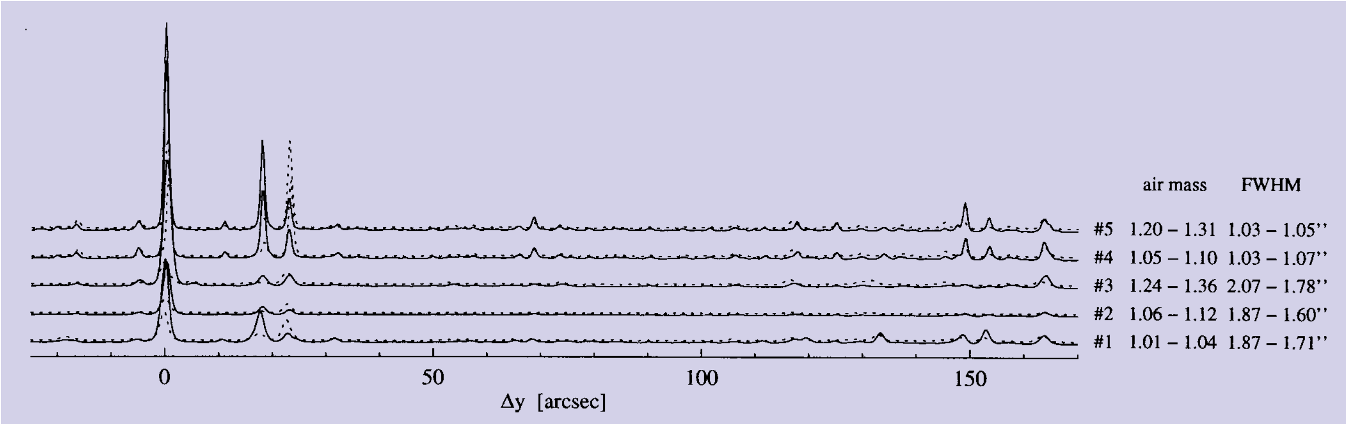

Figure 2: A section of the spatial profiles of five different 97-BLG-56 exposures, those averaged from 4380–4480 Å are dotted, while those averaged from 6350–6450 Å are solid lines. The microlensed target is situated at 0 arcsec but one can see a faint neighbouring star just to the its left, well resolved in exposures #4 and #5. On the right we give the air mass and also the FWHM of the spatial profiles. Since the seeing for exposure #3 was best, it appears that movement of the target along the slit may have caused additional broadening of the spatial profile.

first time that these events presented an exciting opportunity to investigate the formation and evolution of the Galactic Bulge itself. The reasoning goes as follows: Arguably, the most reliable picture that we have for the evolution of the galaxy is based upon very detailed abundance and kinematical studies of nearby disk and halo cool main-sequence stars, similar to the Sun. Unfortunately, such stars in the Bulge are intrinsically too faint for a 3–4-m-class telescope to get even a moderate resolution spectrum with good S/N. However, for the event we studied in 1996 using the NTT, the source was a G-type dwarf undergoing a magnification by a factor of 25 at the time of observation (cf. Fig. 1). The NTT was briefly the largest optical telescope in the world! Even with an 8–10-m-class telescope, such as the VLT or Keck I/II, high resolution and high S/N spectroscopy is out of the question for such intrinsically faint targets. Why not make most efficient use of telescope time and carry out such observations with the assistance of a gravitational lens? Over several observing seasons, and with the help of gravitational microlensing surveys, our aim is therefore to perform a systematic spectroscopic investigation of bulge sources. We expect that the results from this campaign will provide a fundamental insight into the formation and evolution of the bulge of our Galaxy. In the rest of this article we describe our first steps on this road, and summarise the current status of the project.

2. Programme

The feasibility of carrying out a systematic programme of spectroscopic observations of on-going microlensing events was first discussed by the two lead authors early in 1996 while DJL was a visitor to the MPIA. These early discussions received an unexpected boost when DJL, while carrying out another programme at the NTT telescope on La Silla, received a telephone call from Dave Bennett of the MACHO collaboration with the information that a binary microlensing event was *predicted* to undergo a caustic crossing during that observing run! That event, 96-BLG-3, was duly observed by us as a target-of-opportunity and a preliminary analysis has already been published [11]. Note that for an event such as 96-BLG-3, in which the *lens* is a binary system, the light curve may differ dramatically from the standard single lens curve, with the appearance of spectacular spikes as the source crosses caustics or near cusps. Extremely high amplifications may be reached during such occurrences. In Figure 1 we show schematically the timing of our observations compared to a light curve which approximates the behaviour of 96-BLG-3 during the relevant caustic crossing. The MACHO team's prediction of such an exotic event was an impressive feat, further strengthening our belief that on-going microlensing events could and should be spectroscopically monitored. Given this impetus, we therefore submitted a proposal to ESO requesting time on the NTT for a more systematic spectroscopic investigation of microlensing events towards the Galactic Bulge.

We opted for the NTT for a number of important reasons. Chief among these was the expectation that after the 'big bang', some observing on the NTT would be offered in service mode with observations being carried out in queue scheduled mode. Note that ours was not the usual kind of target-of-opportunity proposal, in the sense that we could estimate the expected rate of discovery of new events, as well as their probable range of magnitudes. Our observing programme could therefore be well defined except that we would only have an advance warning of weeks or days, depending on the event duration. Our hope was that we could get the relevant information into the system early enough to allow the NTT team to carry out the observations we required. One additional very important aspect of the NTT is that EMMI is permanently mounted on the telescope, unlike EFOSC1 on the 3.6-m telescope for example. Our only remaining minor concern was that the relevant grism or grating would be mounted in the instrument.

While ESO clearly regard the NTT as an important test of various operational and technical aspects for the VLT, we also saw this programme as a way of gaining valuable experience (for us and for ESO) since we also hope to pursue this work with the VLT. We were therefore extremely gratified that the OPC awarded us 30 hours of NTT time for this project during the period July – September 1997. We were further impressed by the professional assistance of the NTT team on La Silla and the Data Management Division in Garching in implementing and carrying out our programme in what has been a very successful beginning.

3. Current Status

At the time of writing we have data for a total of five events, two were observed previously as targets-of-opportunity, while three events have so far been observed using the NTT and EMMI under our spectroscopic monitoring programme. The events are described below. (We follow the MACHO naming scheme such that 96-BLG-3 refers to event number 3 towards the Galactic Bulge in observing season 1996.)

• 96-BLG-3. A binary microlensing event (the lens is a binary system), the first to be observed spectroscopically. It was observed as the source star traversed a caustic, leading to a very high amplification by a factor of 25 (cf. Fig. 1).

• 97-BLG-10. Another anomalous event with evidence for caustic cross-

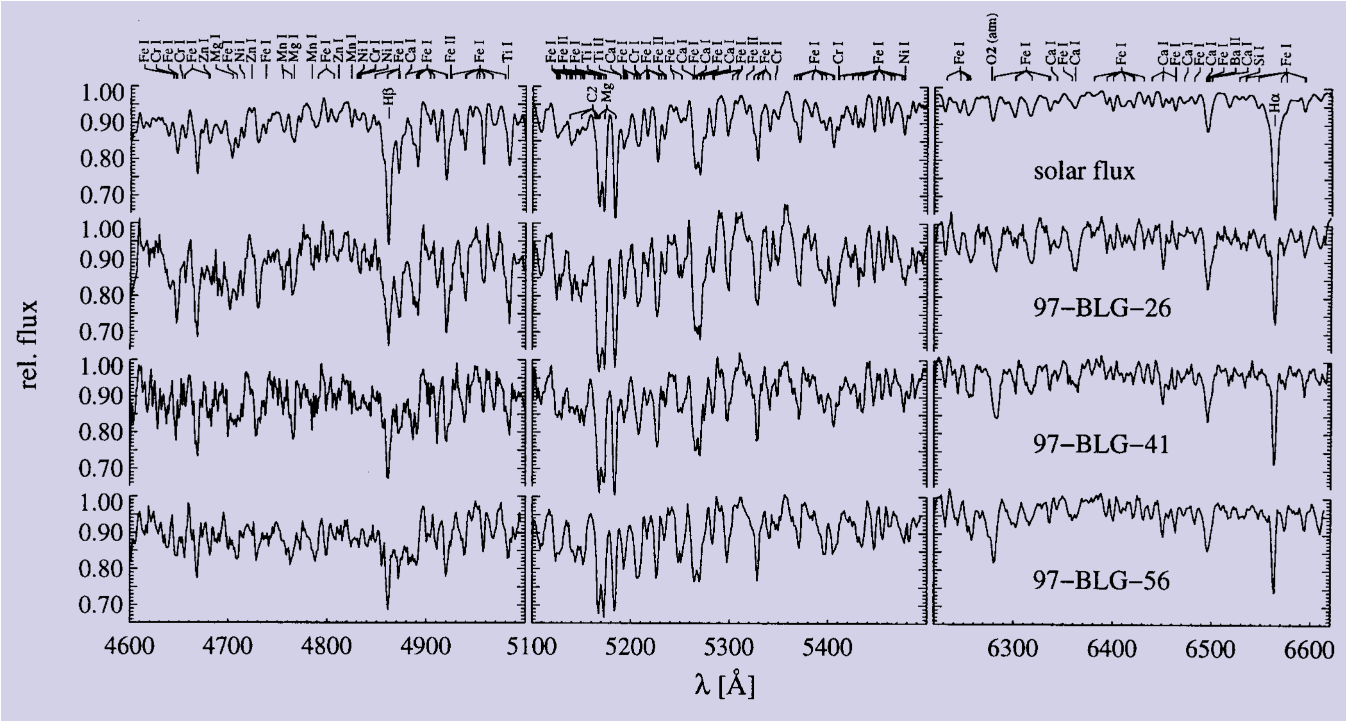

Figure 3: This montage compares the convolved solar flux spectrum (120 km/s Gaussian) with spectrograms of three recently observed microlensing events obtained with the NTT. For all of the observations we used EMMI in RILD mode with grism #5 giving a nominal spectral resolution of 1100 for a 1-arcsec slit and wavelength coverage of 3985–6665 Å. The actual seeing limited resolution is 15% higher. The signal-to-noise ratio of the normalised spectra is ~ 90 (97-BLG-26), ~ 85 (97-BLG-41) and ~ 200 (97-BLG-56). Strong spectral lines are denoted. Telluric absorption lines, particularly O_2 and H_2O at Hα, have not been eliminated, though monitored with white-dwarf exposures.

ings, however the data-reduction process is complicated due to the presence of another nearby star in the aperture of the spectrograph. (Unlike the other events, this was observed at the ESO 3.6-m telescope using EFOSC1 in echelle mode.) Maximum amplification has been estimated as 13.3.

• 97-BLG-26. This was a long-duration, high-amplification event, with a maximum amplification of 8.0, in which the source star is probably a late type sub-giant.

• 97-BLG-41. Another case of an anomalous event indicating that the lens is a multiple system. Again this was observed during a caustic crossing when the source was amplified by a large factor.

• 97-BLG-56. The maximum amplification for this event was also reasonably high (5.5), although the source is intrinsically bright and it is most likely a giant. The expectation here is that one may be able to detect finite source effects such as discussed in [14].

Due to the crowded nature of the fields used for microlensing surveys, plus the requirement that sometimes one is seeking to identify line-profile or continuum-slope variations, the reduction of data is a complicated business which must be performed carefully. This is carried out using a suite of IDL routines developed and maintained at the Universitäts-Sternwarte München. The analysis of these data will be carried out using improved techniques compared to those used by us in earlier work [11].

4. The Challenges

We set ourselves the goal of deriving stellar parameters with typical accuracies of $\Delta T_{eff} \leq 200$ dex, $\Delta \log g \leq 0.3$ dex and Δ[Fe/H] $\leq$ 0.2. The difficulty in achieving this objective using low-resolution spectroscopy of cool stars is illustrated in Figure 4 which shows that the theoretical low-resolution spectra ($R \approx 1300$) are only responding at a level of 3% to variations in gravity and metallicity of 0.5 and 0.3 dex respectively. This means that non-intrinsic features must be either eliminated or excluded from the fit estimation to an accuracy of better than 97%. This makes great demands on the processes of data acquisition, calibration, reduction and spectroscopic analysis. In particular we need to understand the behaviour and properties of the telescope (NTT) and spectrograph (EMMI) used to obtain the data. On the analysis side we have had to develop reliable methods for the interpretation of low-resolution spectra of cool dwarfs and subgiants. In the following we briefly discuss our techniques and some of the problems encountered.

4.1 Data Reduction

The Bulge fields are all very crowded, therefore high *spatial* resolution is important to separate the target spectrum from that of close neighbours. Figure 2 shows spatial profiles (note that we use a long slit) of 5 sequential exposures of 97-BLG-56; it demonstrates that in this case a seeing FWHM smaller than one arcsec is required. Although photometric conditions are not required because we analyse normalised spectra, we need one or more additional stars on the slit to serve as *differential* photometric calibrators to separate intrinsic variations of the continuum slope from those caused by varying transparency, seeing FWHM, airmass, or misaligned parallactic angle. Ideally the calibrator should sit exactly on the slit, providing equal sensitivity to inaccuracies in telescope pointing for both stars; of course the angular distance between both should be sufficiently small to minimise sensitivity to rotator inaccuracies. Figure 2 demonstrates that this has not always been achieved! Nevertheless, we extract all spectra on the slit with a $S/N > 10$, using an optimal extraction technique. We are currently testing a method which allows one to include more than a single profile in the extraction window in order to disentangle spatially blended spectra.

4.2 Spectrum Analysis

We use *line-blanked,* plane-parallel, homogeneous model atmospheres (cf. [17], and references therein). These models (temperature and pressure structures) are similar to those generated with ATLAS9 of R.L. Kurucz, in particular both codes use the standard mixing-length theory to calculate the convective flux. However, we use a

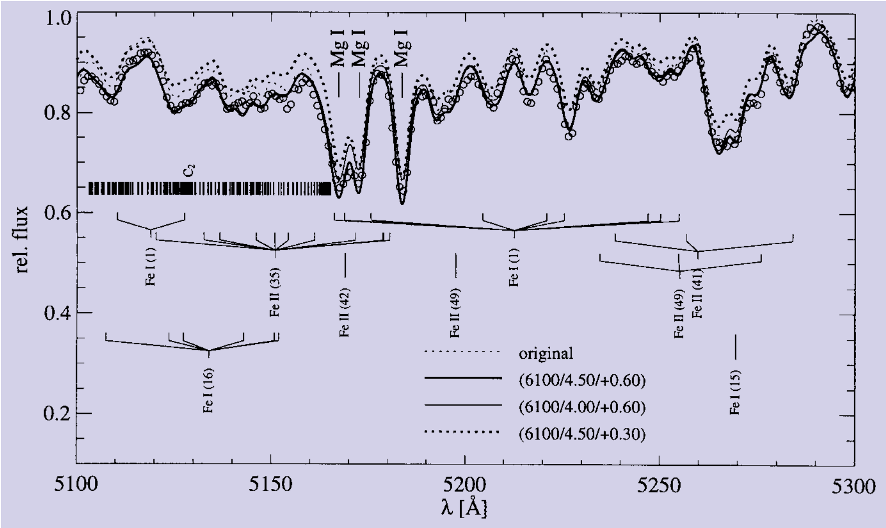

Figure 4: Comparison of synthetic spectra with the previously observed spectrum of 96-BLG-3 (open circles). One improvement over our original work (thin dotted line) [11] is the inclusion of C_2 opacity resulting in a much improved fit bluewards of the Mg I 5167.3 Å component. One can see that the model (T_{eff}/log g/[M/H] = 6100/4.50/ + 0.60) now fits all the data points quite well in this spectral range. Strong iron multiplets are also indicated.

mixing-length parameter that is spectroscopically determined [17], which has some effect on the derived effective temperature. Line opacities are taken into account using opacity distribution functions from Kurucz 1992 [16], scaled to account for the fact that Kurucz' adopted solar iron abundance was overestimated. Atomic and molecular line data originate from Kurucz, except that most of the f-values and broadening parameters have been adjusted such that the line profiles fit the high-resolution solar flux atlas ([15]) in the spectral regions around Hα, Hβ and the Mg b lines (Figure 4).

We determine the *best fit* parameters T_{eff}, log g, [Fe/H], as well as the width of the instrumental profile, presently assumed to be a Gaussian. Synthetic spectra corresponding to randomly selected sets of parameters are interpolated from a pre-calculated grid. A merit function for each set of parameters is then derived which is basically estimated as a χ^2-function, with additional goodness-of-fit criteria used to control the weights assigned to various pixels. Our *Monte Carlo* calculation contains typically a few hundred fit evaluations. The merits are sorted starting with the lowest value which corresponds to the model parameters of the *best* fit, while the fit merits may be used to estimate the uncertainty. As an example, the quality of the fit to the spectrum of 96-BLG-3 is shown in Figure 4. The improvement of the merit function is an important matter of concern in the nearest future, we will also define a physically based strategy to determine error boundaries. A further refinement currently being tested is that of deriving [Mg/Fe] and [C/Fe] abundance ratios.

Finally, we also need to estimate the effect of the lens itself on the perceived flux spectrum of the source since the normal limb darkening law is to some degree distorted by the amplification (cf. the B and R band light curves in Figure 1). (For the present we ignore the possibility that the lens itself contributes significantly to the observed flux.) For example, we know that for the sun the Hα line profile, which is our primary effective temperature diagnostic, is significantly different in centre and limb spectrograms. For 96-BLG-3 we have already computed the effect of the lens on Hα and confirmed that for this object, at the time of observation, the perturbation of the profile is small compared to the uncertainties in the analysis. However, this is of course something which must be considered in general, and is particularly relevant when the source is a giant.

4.3 Preliminary Results

In Figure 3 we show a montage of spectra for the 3 targets observed so far under the auspices of our NTT target-of-opportunity programme. We have derived preliminary stellar parameters for only two of these targets, which are subgiants, since we do not yet have atmospheric models suitable for the analysis of giants. The Balmer line wings presented in Figure 3 indicate effective temperatures of $\sim 5200 \pm 200$ K for 97-BLG-26 and $\sim 5000 \pm 200$ K for 97-BLG-41. Gravities are log $g \sim 3.9 \pm 0.3$ and $\sim 3.2 \pm 0.3$, respectively, whereas 97-BLG-26 appears to be metal-rich ([Fe/H] $\sim$ 0.3 dex) and 97-BLG-41 to be slightly metal-deficient ([Fe/H] $\sim$ –0.2 dex). Due to the high S/N we expect that the uncertainty of the derived metallicities does not exceed 0.3 dex. We have also obtained preliminary radial velocities for other objects falling on the long slit (cf. Fig. 2). The accuracy of the stellar parameters, and therefore the derived radii and stellar masses, are expected to be significantly improved in a more complete analysis.

5. Future Plans

We plan to continue spectroscopic surveys of microlensing events, it is clear that with a sizeable spectroscopic sample one can learn much about the formation and evolution of the Galactic bulge through dynamical and stellar atmosphere studies. The up-to-date status of this project is available at http://www.mpa-garching.mpg.de/~smao/survey.html. It will be very exciting to use the larger telescopes such as the VLT in this work, in fact, the KECK I has already been used to observe the finite source size event 95-BLG-30 [14], and indeed, a more systematic spectroscopic survey was carried out this year (Minniti, private communication). The implications of moving to a larger aperture are obvious; it will be possible to resolve peculiar events with much better time (and therefore spatial) resolution. More subtle events such as blending of light by the lens may become observable with the VLT due to the difference between the lens and source radial velocities. A series of centre to limb spectra could then be used to constrain stellar models of the poorly understood atmospheres of cool giants/supergiants. Microlensing candidates in the LMC and SMC, which are typically fainter by about three magnitudes, come within reach of spectroscopy. In particular, using the VLT and UVES, high S/N and high-resolution spectra will be quite easily obtainable for the more strongly amplified sources such as are discussed above. This will permit the analysis of Bulge dwarfs with an accuracy comparable to that of their nearby field and halo counterparts, and allow us to investigate their chemical compositions in detail, looking at relative abundances of light, α-process, Fe-group, *r*-process and *s*-process elements. The VLT, given its expected flexibility when it comes to scheduling and the wide range of optical and IR instrumentation *permanently* available at its many foci, is ideally suited to this kind of multi-faceted project.

6. Acknowledgements

Carrying out service-mode observing for a project such as ours is not easy, but we at least want to make sure that it is not a thankless task! Special thanks are due to the staff at La Silla including Gauthier Mathys, Chris Lidman, G. van de Steene and the rest of the NTT team. We also thank ESO staff at Garching, particularly Dave Silva and Albert Zijlstra in the Data Management Division for their professional assistance. Of course, this work would not be possible without the real-time alert system of the MACHO collaboration and the photometric follow-up networks of the PLANET and GMAN collaborations. We have also benefited from discussions with the EROS and OGLE collaborations. We are indebted to Dave Bennett, Chris Stubbs and Charles Alcock (MACHO), Penny Sackett (PLANET), and Jim Rich (EROS) for discussions and encouragement.

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LATEST NEWS:

The First M2 Unit and Beryllium Mirror Delivered to ESO

S. STANGHELLINI, ESO

At the time this edition of the *Messenger* went to press, the first M2 Unit and the first M2 Beryllium mirror of the VLT have successfully passed the final and most critical phase of their acceptance testing in the integration hall of Dornier Satellitensysteme in Friedrichshafen, Germany. This closes a period of more than seven months of severe tests performed to guarantee that the Secondary Unit and its mirror meet the stringent requirements necessary to ensure the full optical quality of the VLT. This period was characterised by a close interaction between the Dornier and the ESO team following the project[1] to establish the complex test procedures and to review the results.

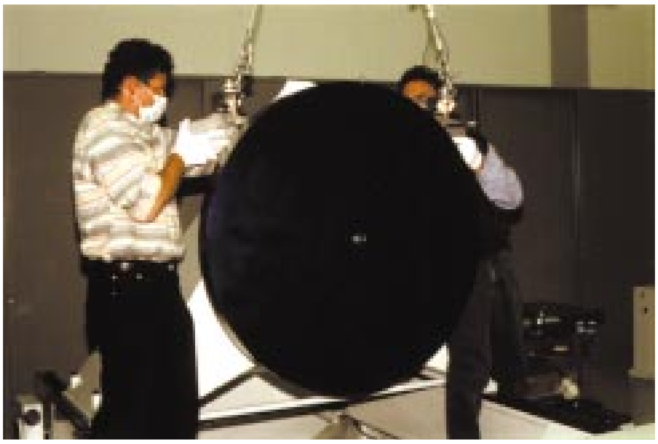
The test programme started in May 1997 with the tests of the software, closely followed by the tests of the electromechanical unit, done with the help of a lightweighted dummy mirror. The test results, although successful, led to a number of improvements and optimisations, performed by Dornier during the following months.

During the same period, REOSC Optique in Paris was completing the final polishing of the first Beryllium mirror, which after integration of its titanium support system, and following optical tests, was delivered to Dornier in September 1997.

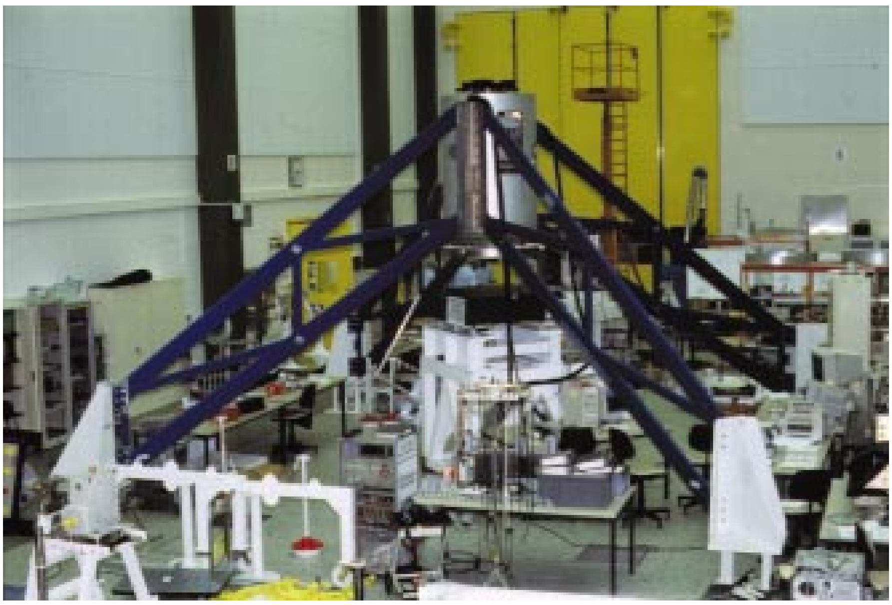
Here, the M2 mirror was dynamically tested to determine its inertia and the position of its centre of gravity, crucial elements for the proper balancing of the chopping mechanism. In October, the M2 mirror was inserted for the first time in the M2 Support Unit to check the differences between the dummy and the real mirror. In November, finally, a test set-up with real telescope spiders that carry the M2 and its support was prepared and assembled in the integration hall of Dornier. Due to the flexible mounting, it was possible to detect any unbalance in the M2 Unit that might possibly affect the telescope pointing.

These final tests were successful and have now led to provisional acceptance of the M2 Unit. They have not only shown full compliance with the ESO chopping and tip-tilt (*field stabilisation*) requirements, but have also demonstrated the feasibility to tune the system for active rejection of unwanted mechanical resonances.

It is therefore expected that the M2 Unit will be successfully integrated in the first VLT Unit Telescope. At the time this note is being written, the M2 Unit is being packed and will soon be shipped to Paranal in its special container.



The M2 Beryllium mirror in the test laboratory of DASA, Ottobrunn, Germany, during the determination of its inertia and centre of gravity. The mirror is protected by a peelable protective layer.



The M2 Unit with the Beryllium mirror at Dornier during the spider tests. The mirror is in front of the granite block used for the testing. The spider structure is anchored to the floor by means of dedicated interfaces, simulating the attachment to the top ring of the telescope.

[1] The ESO team involved in the acceptance of the M2 Unit is composed by the author and by G. Jander, A. Michel, M. Duchateau, B. Gustafsson, P. Giordano, W. Ansorge.