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TIGRE: A new robotic spectroscopy telescope at Guanajuato, Mexico

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TIGRE is a new robotic spectroscopy telescope located in central Mexico at the La Luz Observatory of the University of Guanajuato. The 1.2 m telescope is fiber-coupled to an échelle spectrograph with a spectral resolving power exceeding 20 000 over most of the covered spectral range between 3800 Å and 8800 Å, with a small gap of 130 Å around 5800 Å. TIGRE operates robotically, i.e. it (normally) carries out all observations without any human intervention, including, in particular, the target selection in any given observing night. In this paper we describe the properties of the TIGRE instrumentation and its technical realization, as well as our first operational experience with the performance and efficiency of the overall system. Finally, we present some examples of recent TIGRE observations.

1 Introduction and overview

Imaging, spectroscopy, and monitoring are among the classic tasks of observational astronomy. Since astronomers cannot truly experiment with their objects of investigation, monitoring (often over long time scales) plays an important role, because only systematic observations reveal the behavior of a given source in the time domain and may reveal the underlying physical processes. The minimal time scale τ of variability is given by $\tau = L/c$, with L denoting the characteristic source size and c the speed of light, but clearly, variability can also occur on any (much) longer time scale.

The longest known astronomical time series is probably that of the sunspot cycle, which dates back to the times of Galileo and Scheiner in 1610. The availability of photometry on archival photographic plates allows the construction of light curves over approximately 100 years, albeit the selection of sources is typically quite random, and the data quality quite mixed.

One of our main scientific interests lies in stellar analogs to the solar activity cycle, which can be studied, for example, by means of their variable emission in the Ca II H & K line cores. These line core emission reversals seem to have been first described by Eberhard & Schwarzschild (1913), and it is now well established that in the Sun and solar-like stars this line emission is caused by bright chromospheric "plage" regions. Further, these emissions vary both with stellar rotation and stellar activity, and long-term monitoring provides extremely valuable insights in stellar activity cycles, as shown in the landmark papers by Wilson (1978) and Baliunas et al. (1995). The observations reported in these papers were carried out with the Mt. Wilson H & K photometer in the traditional way, i. e., with astronomers personally carrying out the observations and reducing the data. Similar considerations apply to massive stars, where regular access to stable instrumentation leads to an improved understanding of spectral variability, especially for the slowly-rotating magnetic O-stars, and to the detection of hitherto unknown multiple systems. Again, the typical time scales of variability in these objects are days to months, sometimes even years, thus requiring a new observational approach.

Advances in telescope, computer, and internet technology nowadays allow the possibility of other solutions for such repetitive observational tasks, which are far more economical and far more efficient than the traditional approach. A special aspect of interest to a small university institute is the unique access to a data set which cannot be obtained otherwise. TIGRE, the acronym stands for Telescopio Internacional de Guanajuato Robótico Espectroscópico, is a fully robotic 1.2 m telescope located at the La Luz Observatory (central Mexico) of the Department of Astronomy of the University of Guanajuato (UG). The TIGRE project is run by astronomers from Hamburger Sternwarte (HS), from Guanajuato (UG), and the High Energy Astrophysics group of the University of Liège (UL). HS contributed the telescope, the spectrograph and the system software, UG and UL the necessary infrastructure, and UG is responsible for maintenance of its La Luz site.

The 1.2 m TIGRE telescope feeds a high resolution spectrograph which covers most of the optical spectrum

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Fig. 1 TIGRE at La Luz Observatory, Guanajuato, Mexico; copyright tau-tec GmbH.

between 3800 Å–8900 Å with a spectral resolving power $\lambda/\Delta\lambda$ of about 20 000. The spectral data is reduced by an automatic data reduction pipeline and is available for scientific analysis usually one day after data acquisition. The telescope operation is fully automatic, with the system choosing its targets from an object list, based on sky availability and – of course – the priorities set by the observer. Figure 1 gives an impression of the site and the whole facility. La Luz Observatory, is located at 21.05329 degrees north and 101.32510 west, at an altitude of 2400 m above sea level on a high plateau north of the city of Guanajuato (elevation: 2100 m).

Like most of Mexico, Guanajuato has very distinct dry and wet seasons, January and August usually being the driest and wettest month, respectively, yet the temperature essentially never falls below freezing. The dry winter climate, while otherwise offering the best observing conditions, comes with strong dust production. Therefore the telescope is actually mounted more than 3.5 m above ground to escape the worst pollution (cf. Fig. 1). The whole design is compact, and the two building extensions contain an air-conditioned spectrograph room (right extension in Fig. 1) and the housing of the electric cabinet and oil pumps (left extension in Fig. 1).

Here we present a description of the overall project, the telescope and spectrograph hardware, the various software used for system operations, and discuss the system efficiency and data quality according to the spectroscopic data obtained in the first months of regular operations in Guanajuato.

2 The TIGRE hardware

2.1 The TIGRE telescope

The 1.2 m TIGRE telescope (originally referred to as "Hamburg Robotic Telescope") was manufactured by Halfmann Teleskoptechnik GmbH (Germany) and delivered to the University of Hamburg in 2005. It was at first installed at Hamburg Observatory, where the performance of the telescope and software was thoroughly tested as described by Mittag (2006). These studies yielded limitations dominated by the limited Hamburg sky quality and seeing rather than by the telescope itself. In the following years the telescope served mainly as testbed for the development of the software for a fully automatically operating system of telescope, spectrograph, and all auxiliary equipment like the dome and weather stations. Finally, in order to demonstrate the full system, a robotic program of stellar spectroscopic observations of solar-like stars was started at Hamburg Observatory before shipping the telescope to its final site at La Luz Observatory in Guanajuato, Mexico, in September 2012.

The telescope is of the Cassegrain-Nasmyth type, where the Nasmyth M3 mirror is rotatable, realizing foci at either side of the elevation axis; however, at present only one Nasmyth focus is in use by the spectrograph HEROS (see Sect. 2.3). The main parabolic mirror, M1, has an aperture of 1.2 m with a primary focal length of 3.6 m. The secondary Cassegrain mirror, M2, lengthens the telescope focus to 9.6 m, making it an f/8 system; all mirrors are made of Zerodur. M1 is relatively thin (aspect ratio of 10), and so requires an actuating cell support system, consisting of multiple static lever support arranged in two axial rings containing 6 and 12 levers, each, and there are 12 levers for lateral support mounted at the mirror edge. The optical image quality is characterized by a spot concentration of at least 90 % falling into less than $1''$ on the optical axis. This light concentration is realized over a FOV diameter of 6 arcmin. The analysis of a defocussed stellar image by the optics manufacturer Carl Zeiss Jena GmbH even suggested a light concentration of 80 % in $0.35''$ on the optical axis, where spectroscopic observations are carried out. Thus the light gathering power of the telescope is practically limited by seeing only.

The telescope is carried by a very rigid and compact alt/az mount, which requires only a small dome (6 m diameter at La Luz). The bearings are hydraulic in azimuth, but mechanical in elevation. A special feature are the direct drives controlled by high-precision absolute encoders, guaranteeing a backlash-free, high-precision pointing and tracking as well as a high slewing speed of 5 degrees per second. The high-precision pointing to celestial coordinates requires a pointing model, which is taken from the encoder readings of approximately 100 stars distributed over the sky, compared with their catalog positions.

The pointing model of the TIGRE telescope uses 15 parameters, 5 more than the 10 standard parameters. Unfortu-

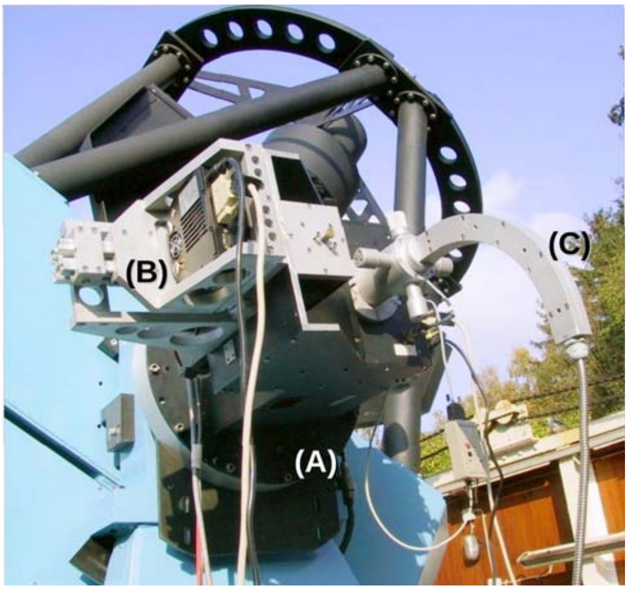

Fig. 2 The TIGRE adapter. A: Nasmyth platform of the telescope; B: the adapter with the flanged guiding camera in the foreground; C: Fiber holder with the fiber inside a protective tube.

nately, some of these are temperature dependent (for details, see Mittag et al. 2008). To estimate this effect we measured the pointing model several times over the year. The results were included in the telescope control software and lead to a stable pointing accuracy of approximately 5″ rms. Measuring a single pointing model takes about half a night and is fully automatic.

A good pointing of the telescope is the basis for an exact tracking. The tracking error lies in the order of only a few arcseconds per hour without any autoguiding. When the autoguider is switched on, the residual guiding error only depends on seeing and is reduced to a few tenths of an arcsecond averaged over the duty cycle of 10 seconds (see description in Sect. 2.2).

2.2 The TIGRE adapter

The basic function of the TIGRE adapter is to feed the light from either a star or from the calibration lamps into the spectrograph. Figure 2 shows the telescope's Nasmyth platform, the actual adapter mounted, and the fiber holder protecting the fiber inside. The telescope is optically coupled to the spectrograph via a fused silica multi-mode fiber with a core diameter of 50 μ, a core/cladding ratio of 1.2 and a step index profile. In order to adapt the numerical aperture of 0.22 of the fibre to the focal ratio of f/8 of the telescope on the entrance side, and to the focal ratio of f/4.5 of the spectrograph collimator on its exit, both ends of the 15 m long fiber are equipped with integral microlenses. These microlenses were formed from the fiber material itself; this special laser-based technology was accomplished by EFO-QUARZ GmbH (Switzerland) to minimize any light losses.

Originally the fiber entrance was embedded in a tilted mirror design, where the focal plane around the fiber was

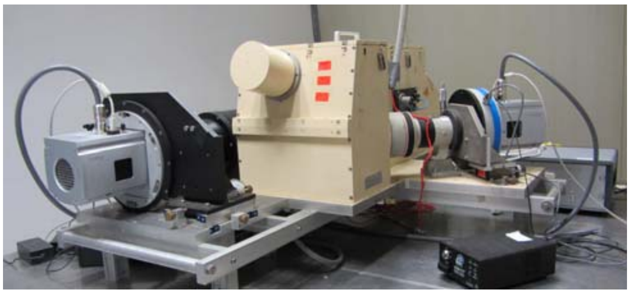

Fig. 3 The "new" HEROS at La Luz Observatory.

imaged by an extra acquisition camera. Later, a better solution was developed for a more precise acquisition and guiding. Now, 8 % of the light of the entire focal plane is reflected by a 45° tilted pellicle beam splitter and imaged by a SBIG ST7 CCD camera. The latter is adjustable in three axes for raw alignment (only done during maintenance). In order to find the exact position of the stellar image on this camera, when the remaining 92 % fall into the fiber, a scanning procedure in alt-az is automatically performed during evening twilight with a very bright star, searching for maximum signal in the spectrograph. A similar procedure is then performed to find the best focus. In both cases, the signal of the spectrograph is normalized by the reading of the stellar counts in the guiding camera, in oder to evaluate its strength regardless of sky transparency. The focus position is changing during the night because of temperature changes. The relationship between the relative change of the temperature and focus position was measured once during the commissioning phase and then implemented in the control software of the telescope making a correction automatically for each stellar observation.

The exposure time of the guiding camera is fixed to 10 s during the guiding process to properly average over seeing motions. The large dynamical range of guide star brightness is therefore handled by neutral filters of different density, which are inserted before the guiding camera by means of a filter wheel. The adapter has a direct computer link to the telescope (bypassing the CCS, see Sect. 3.1), sending the corrections to the positioning immediately to the telescope.

The adapter also houses the light sources for the spectrograph calibrations. These are a tungsten lamp for flat-fielding and a ThAr hollow cathode lamp for the wavelength calibration. Either light source can be electronically switched into the beam to the fiber.

2.3 The TIGRE spectrograph

Currently the only focal plane instrument of TIGRE is the fibre-fed échelle spectrograph which was built by refurbishing the HEROS (Heidelberg Extended Range Optical Spectrograph) spectrograph; a detailed description of the original spectrograph can be found under the URL http://www.lsw.uni-heidelberg.de/projects/instrumentation/Heros/. The "new" HEROS now used at La Luz Observatory and fed by the TIGRE telescope is shown in

Fig. 3. Compared to the "old" HEROS, which had already been used successfully for various monitoring campaigns, there has been a refurbishment, a new cross disperser grating for the red channel was introduced, blazed at 750 nm, and, most notably, two new Peltier-cooled ANDOR CCD cameras have been acquired (see Fig. 3), which are indispensable for robotic operations. The "old" HEROS was still run with CCDs cooled by liquid nitrogen, requiring frequent manual refills.

We specifically chose an ANDOR iKon-L DZ936N-BBB for the blue channel and an ANDOR iKon-L DZ936-BV for the red channel. Both cameras are equipped with E2V 2k×2k chips, which have a pixel size of 13.5 μ and are thinned and back-illuminated. The deep Peltier cooling suppresses the dark current to a level of 1e$^-$/pxl/h, so that the instrumental accuracy is dominated solely by the read-out noise. The latter reaches 7e$^-$/pxl, when the read-out frequency is set to achieve a read-out time of only a few seconds. The measured quantum efficiency of the chips is 80 % at 3900 Å and increases to 93 % at 6000 Å; at 8500 Å the cameras still have a quantum efficiency of 50 %, assuring TIGRE a sufficient sensitivity at the Ca II infrared triplet.

The two-channel échelle spectrograph is located in a separate, climate-controlled room and fed via an optical fiber with integrated f/4.5 couplers. Inside the spectrograph, the light first passes the collimator, then the échelle grating. Behind the latter, it is split into two light beams (blue and red light) via a dichroic beam splitter. The blue light beam covers a wavelength range of ≈ 3800–5700 Å and the red beam a wavelength range of ≈ 5830–8800 Å. Each light beam then passes its own cross disperser grating and is imaged by its own optics and CCD. This system provides a relatively constant spectral resolution of $R \geq 20\,000$, only at the very shortest wavelengths it drops to ≈ 19 800 (see Sect. 4.2 for more details).

2.4 Infrastructure for TIGRE at La Luz Observatory

The concept of TIGRE as an autonomously operating, robotic telescope, with the need of permanent communication to and from the outside world for control and data transport, strongly depends on a reliable supply of electricity and internet. Such requirements are not easily fulfilled in rural central Mexico. The site of La Luz Observatory is located in a relatively remote area, where electricity supply is a rare commodity, and the existing power line to the observatory, which used to deliver only two phases of 127 V, suffers from frequent failures and interruptions, as well as from voltage irregularities, mostly related to thunderstorms and insufficient regulation of the variable consumer load. An internet supply through optical fiber does not exist, neither is the observatory within reach of a mobile telephone communication network. Further, but by comparison smaller problems are the need of European three-phase 230/400 V electricity supply for the German-built telescope and a well controlled temperature environment for the spectrograph, where outside conditions vary between near freezing night temperatures and intense solar exposure during the day. In short, the TIGRE system presents the challenge of establishing European 21st century technology in a rather remote environment.

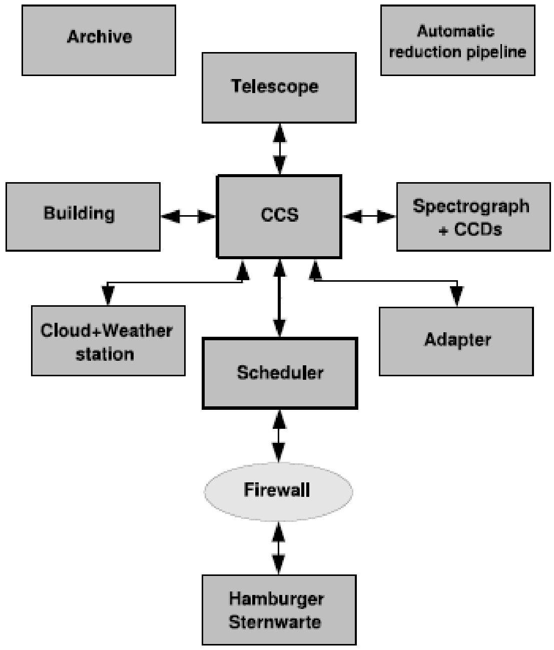

Fig. 4 Overview of the TIGRE software system.

The University of Guanajuato has solved these problems by the following infrastructural measures: (i) installation of a microwave beam internet connection to a server on the Cristo Rey peak less than 10 km away, (ii) extension of the existing power line to a third phase, (iii) a fuel-operated 100 kW power plant, which automatically starts within seconds whenever the external electricity supply fails, (iv) a large lead-gel battery assembly supporting a large power regulator unit (UPS), which regulates the voltage and is an additional back-up to the electricity supply of the observatory for at least 30 minutes under nominal telescope operations, (v) an insulated and air conditioned spectrograph cabinet, and (vi) a 3-phase transformer from 127/220 V to 230/400 V. Since only the oil pump strictly needs a frequency of 50 Hz, this unit is backed by a small frequency transformer 60/50 Hz, while the rest of the equipment operates on the US-Mexican 60 Hz standard.

3 The TIGRE software

3.1 The TIGRE system software

A robotic telescope like TIGRE requires a sophisticated software system, yet at the same time, the software should be as simple as possible. We have therefore chosen a modular concept where the control software of all system parts are entirely separate programs, which communicate through TCP/IP ASCII messages. The overall system software structure is shown by Fig. 4. The Central Control System (CCS) leads the hierarchy, it definitely is the core of our software and controls all other subsystems, which correspond to the different parts of TIGRE: One system controls the telescope, another the building, another has the purpose of monitoring the weather conditions such as wind direction and speed, precipitation, sky temperature, cloud coverage etc., another controls the adapter and the TIGRE spectrograph. Further, two parts of the software are related to the archive which contains all CCD images and a protocol of all TIGRE operations, and to the Automatic Reduction Pipeline, described in Sect. 3.2.

The system has two operational modes: In the interactive mode a human operates the CCS, while in the robotic mode the CCS itself decides what to do. However, in both cases the same collection of commands is sent to the subsystems, which always operate in the same fashion. The whole software is almost completely written in Java under Linux. An exception is the software for the CCD cameras used in the adapter and the spectrograph, which analyzes the digital images. This software is written in C and integrated in the Java software using the Java Native Interface.

A typical TIGRE observing run proceeds – roughly – as follows: First, the whole system, except for the telescope, is initialized before sunset, well before the start of observations. Then bias and flat fields are taken as well as ThAr images with the spectrograph cameras. Weather permitting, the dome is opened after sunset and the telescope is initialized. This is followed by the start of night calibrations such as focusing and searching for the entrance position of the fiber on the guiding CCD – i.e., calibrations, which can only be carried out with the help of real stars. After this the scientific observations are started, if weather conditions are still suitable.

The first command of this procedure requests a new target from the scheduler. As the procedure is repeated, (usually) a new and different target is selected. Thus, although the robotic operator formally repeats the same procedure, different observations are actually performed. The information message about the new target contains not only the name, positions, and properties of the star, but also the type of observation, which may be a scientific or an engineering measurement, e.g. pointing model observations, or additional calibrations. Before sunrise the telescope is shut down and the dome is closed. Some further calibrations are still carried out, then all subsystems are shut down.

A variety of diagnostic instruments are available to assess and monitor TIGRE through various weather stations, i.e., web cams and a sensitive sky monitor constantly monitoring the visible sky immediately above La Luz Observatory, which shows all stars down to about 4th magnitude. However, we have found that the best method to assess the observing conditions is by continuous measurements of the sky temperature (recording its IR radiation), relative to the ambient temperature; in addition the measured values for wind speed and humidity are also taken into account and must stay within predefined limits.

Provided wind properties and humidity allow observations, TIGRE starts observing if and when the relative sky temperature has dropped below –30 °C. If the sky temperature rises above this threshold, the dome is automatically closed and the system waits for stable weather conditions. In order to avoid operational instabilities, the dome stays closed for at least 15 minutes before it may reopen, weather (resp. relative sky temperature, wind and humidity) permitting. During a night with cloud fields passing through the dome is multiply opened and closed; this feature provides a gain more than 1/3 of overall observing time at La Luz, in particular outside the dry season.

3.2 The TIGRE data reduction pipeline

A robotic telescope system produces a large amount of data. Therefore, a "manual" data reduction is completely out of the question. Consequently, the standard data reduction pipeline of TIGRE is a fully automatic data reduction pipeline including an automated wavelength calibration. The pipeline is implemented in the IDL (Interactive Data Language) environment and uses the powerful and flexible reduction package REDUCE (Piskunov & Valenti 2002), with special adaptation to the HEROS context. The pipeline is started automatically after the data transfer from La Luz Observatory to Hamburg has finished. The reduction process includes all standard and necessary reduction steps for échelle spectra.

In addition, log files are generated during the creation of the master calibration images (bias, dark, and flat field) to monitor the stability of the CCD cameras and flat field lamp. A dark correction is not necessary, because the dark noise is much lower than the readout noise, and the mean dark level is removed during the background correction. Flat-fielding makes use of a tungsten lamp spectrum. Finally, standard star spectra are used to compute a correction function, which is used to remove remaining residuals from the blaze correction of the spectra.

In the case of problems during the data reduction, an error message is created and the reduction of the affected spectrum is stopped. If an error occurs during the creation of the master calibration images then the whole reduction process is stopped completely. Furthermore, the pipeline will merge several spectra of the same source obtained in a given night unless it is told not to do so.

For the automatic wavelength calibration the spectra of the ThAr lamp are used. These spectra are taken before and after the observations. The extracted ThAr-spectra are cross-correlated with a reference spectrum to determine the mean wavelength shifts. With this mean shifts and the values of the line positions of the reference spectrum the new wavelength solution is estimated. All results of the reduction process are saved in FITS files and are available for further, "manual" analysis. Of course, a complete re-reduction of the data by an observer is also possible since all "raw" data as well as calibrations are stored.

3.3 The TIGRE archive

Under optimal conditions TIGRE can take more than 1000 individual observations with more than 250 hours of total exposure time per month. Given the large amount of data produced by TIGRE an archive system is required as an interface serving an easy access and navigation of all TIGRE data. Furthermore, we opted for an integral system, which not only stores and indexes the observations, but which also allows the users to introduce their proposals and the targets to be observed, and to follow which observations have already been carried out by TIGRE. In this way the TIGRE archive also serves the management of the proposals and supports the daily operation of the telescope and the quality control. It thus gives the astronomer more control of what TIGRE should do and helps to take responsibility for the quality of the observations.

This archive software has three parts. Its core is a mySQL database that contains the information from the users, proposals, characteristics of the targets and required observations as well as the paths to the raw and reduced spectra and quality parameters of the observations. In the future, technical information describing the course of the night and the status of the system will be also stored there. The user interface, the second part, has been written in PHP and is accessible through a web page. Finally, the telescope interface, used mainly by the scheduler, is still under development and is written in Java.

4 TIGRE performance

4.1 Observatory

Although the TIGRE Observatory concept looks entirely fool-proof on paper, the often violent electrical thunderstorms of the rainy season and the creativity of adverse circumstances have taught us many lessons to the contrary. The main conditions to be handled are: (i) Nearby strikes of electrical discharges introduce voltage spikes by induction, reaching beyond the UPS. This sometimes causes the electrical fuses of the air conditioning and the main control computer of the telescope to shut down. (ii) The outside electricity does not switch off cleanly, but on failure rather resurges several times, thus confusing the sensor of the power plant, which consequently often fails to start, leaving the observatory to run only on the batteries. Once discharged, the power supply system requires a manual restart. (iii) The internet and thus control over the instruments fails of course when the electricity supply fails, i.e., when the capacity of the batteries has run out. Sometimes, bad weather can also cause a power cut to an essential regional server of the university or of the Mexican Telecom, or strong traffic down the line can reduce communication to and from the TIGRE instruments to unacceptably low levels.

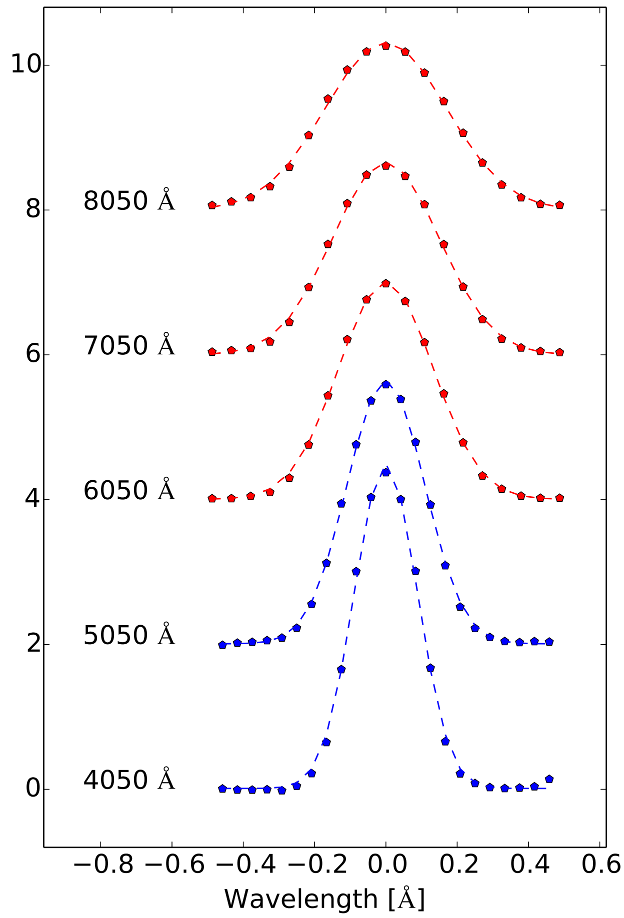

Fig. 5 Some examples of TIGRE calibration line profiles covering the whole spectral range. While the absolute width of the spectral lines increases with wavelength, the relative width decreases, leading to a slightly increasing spectral resolution with increasing wavelength.

4.2 Spectral resolution, data quality, and throughput

Obviously the main characteristics of our TIGRE-system are the actual spectral resolution achieved, the quality of the data in terms of SNR and spectral stability and the throughput of the system, which in the end defines the scientific phase space accessible to the system.

Let us first consider the spectral resolution obtained by TIGRE. In Fig. 5 we plot the observed widths of calibration lines from the ThAr lamp as a function of wavelength, fitted by Gaussians. Obviously, Gaussians provide a very good description of the instrumental profiles, and the derived widths allow us to characterize the wavelength-dependent spectral resolution displayed in Fig. 6 for the two arms of the spectrograph. The spectral resolution increases with wavelength and there is a small jump between the blue and red arm. Nevertheless we can state that the spectral resolution exceeds 20 000 for all wavelengths above ≈4500 Å, and in the range of the important Ca II H & K lines the spectral resolution is slightly below 20 000.

We also inspected the accuracy of the wavelength solutions in the two arms using the residuals of several

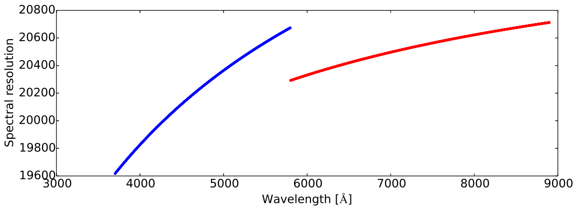

Fig. 6 TIGRE spectral resolution as determined from ThAr calibration lines in the blue arm (blue curve) and red arm (red curve).

hundred ThAr calibration lines and found dispersions of $\approx 135\,\mathrm{m\,s^{-1}}$. However, this number refers to the internal accuracy of the wavelength solution. Since the spectrograph is still subject to some moderate temperature and all pressure variations on the site and since wavelength calibrations are (normally) carried out only at the beginning and end of the night, the actual accuracy is determined by hitherto uncorrected for drifts which are under investigation.

The achievable SNRs obviously depend on the spectral energy distribution of the source and the sky conditions. To assess the data quality of individual nights we regularly observe standard stars like the bright star Vega (m_v = 0.03) with typical exposure times of 1–2 s. TIGRE spectra can be rebinned by a factor of two without compromising on spectral resolution, and for a 9-mag star we typically achieve a SNR of 100 at 6100 Å in an exposure time of slightly above 30 min. Since the viewing conditions can appreciably change from night to night and even during a given night, we have found it necessary to implement a feature that adjusts the exposure to achieve a pre-set SNR to guarantee a user-defined data quality.

4.3 System efficiency

Our present experience has shown that the whole system can operate very efficiently the weather and infrastructure (electricity and internet) permitting. It is not exactly clear how one should measure the efficiency of a robotic telescope system. Such a measure of efficiency could be the total scientific exposure time per night or the number of spectra of different objects taken; the first measure could be optimized by taking long exposures of the same target, the second by taking short exposures of as many bright objects as possible. Obviously any consideration of the system efficiency cannot be separated from the scientific observing program and its requirements and priorities. At any rate, since TIGRE typically carries out repeated observations of the same target(s) and since the observing conditions with regard to sky transparency and air mass usually change, we have found it absolutely necessary to adopt a procedure that automatically adjusts the exposure to a given predefined SNR in order to avoid either overexposure under optimal observing conditions or underexposures with low SNR in poorer conditions.

In order to give an impression of the system performance in terms of total scientific exposure time per night and number of targets per night, we consider here the first

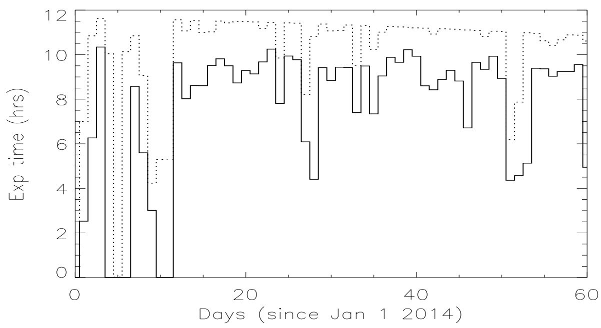

Fig. 7 TIGRE efficiency as measured in terms of hours of exposure per night (solid histogram) in comparison to total available time (dotted histogram); during good nights the TIGRE system reaches more than 90 % efficiency.

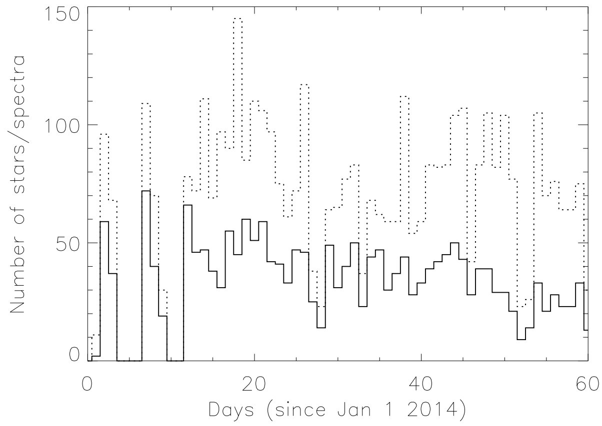

Fig. 8 TIGRE efficiency as measured in terms of obtained spectra per night (dotted histogram) and stars observed per night (solid histogram); as can be seen, the system has no problem observing more than 70 different objects per night.

two months of 2014, when we encountered very stable observation conditions. In Fig. 7 we plot the nightly cumulated scientific exposure time (in hours per night, solid histogram) as a function of day number compared with the actually available time (i.e., relative sky temperature below -30°C, dotted histogram). Figure 7 clearly shows that the system can utilize the available observing time with efficiencies exceeding 90 %. In Fig. 8 we consider the number of recorded spectra (dashed histogram) and observed stars (solid histogram) per night. While clearly the number of recorded spectra could be a misleading figure, if the spectra are all taken from the same object, Fig. 8 also shows that during some nights more than seventy different stars were observed; this implies that with every new star observed a new re-pointing and acquisition maneuver had to be carried out successfully.

4.4 Examples of TIGRE science data

We now present some example science data which demonstrate the capabilities of TIGRE, beginning with the red

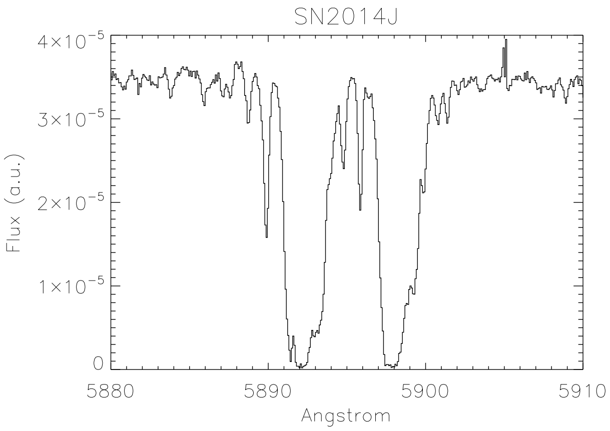

Fig. 9 TIGRE spectrum of the Na doublet at 5895.92 and 5889.95 Å (rest wavelength). The interstellar absorption is red-shifted, indicating that it originates in M 82, and its main component is highly saturated.

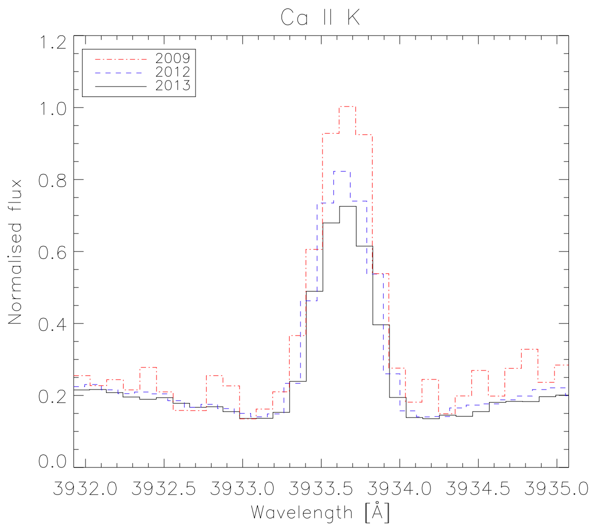

Fig. 10 TIGRE spectra of the Ca II K line core of 61 Cyg A taken in 2009, 2012, and 2013. Note the decline in the core emission strength with the declining cycle of 61 Cyg A, as well as the much improved spectral quality of the data taken since 2012.

spectrum of the supernova SN 2014J in M 82 ($m_v \sim 11$), which was extensively monitored by us in the weeks following its discovery. Figure 9 shows the Na I interstellar absorption line in M 82. While the rest wavelengths of this doublet are at 5895.92 Å and 5889.95 Å respectively, the observed wavelengths do not correspond to the redshift of M 82, but are blue-shifted relative to the center-of-mass velocity of M 82. This demonstrates that a substantial amount of gas in the line of sight is rotating towards us in M 82, showing that the supernova SN 2014J exploded on the "far" side of its host galaxy. The typical TIGRE exposures of SN 2014J were 3 hours and resulted in typical SNRs of about 90. Clearly, the magnitude range of 11–12 mag is the faint limit, where TIGRE monitoring campaigns can be reasonably performed.

We continue with the TIGRE performance at the Ca II H & K lines. As pointed out before, activity monitoring is one of the key science areas envisaged for TIGRE observations and therefore optimum fiber through-put, especially in the near UV, is of utmost importance. Figure 10 shows a series of Ca II spectra of 61 Cyg A. 61 Cyg A and 61 Cyg B form a visual binary system and are both chromospherically (Baliunas et al. 1995) and coronally active (Hempelmann et al. 2006). The A component has one of the best defined stellar activity cycles with a duration of about 7.3 years (as shown by Baliunas et al. 1995) and also displays an X-ray cycle in phase with the chromospheric cycle (see Robrade et al. 2012). In Fig. 10, we specifically show spectra with exposures of 12 min obtained in the years 2009, 2012, and 2013. This was in the declining phase of 61 Cyg A's activity, which is also evidenced by its X-ray properties (cf. Robrade et al. 2012). Also well visible in Fig. 10 is the dramatically improved SNR of the two more recent spectra, which were already obtained with our new blue-sensitive ANDOR CCD camera (see Sect. 2.3).

Owing to its flexibility in scheduling, TIGRE is also a powerful tool for ground-based support of space observa-

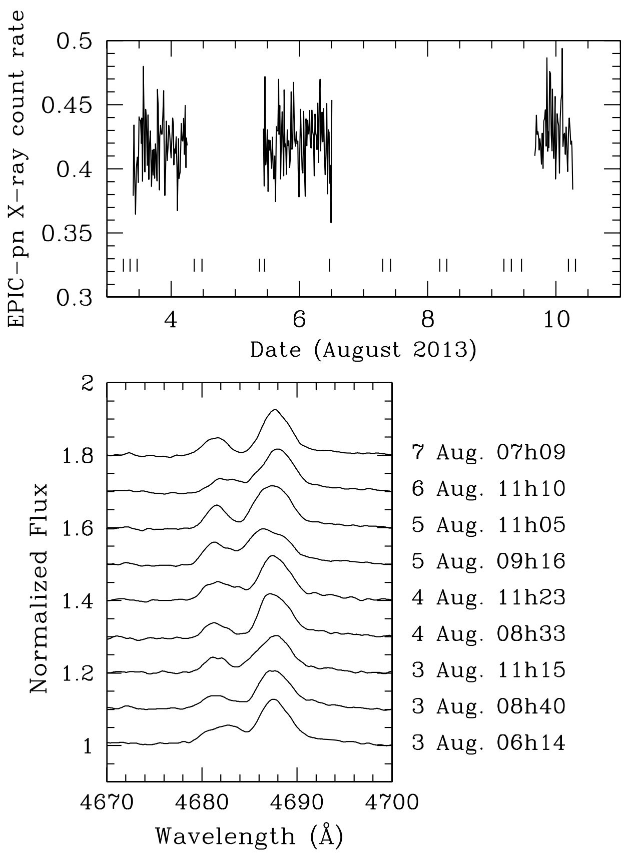

Fig. 11 Simultaneous X-ray and TIGRE observations of λ Cep. The *top panel* illustrates the raw X-ray light curve recorded with the EPIC-pn instrument aboard XMM-*Newton*. The tickmarks correspond to the times of the TIGRE observations. The *bottom panel* illustrates some examples of the He II λ 4686 Å emission line profiles of λ Cep observed with TIGRE.

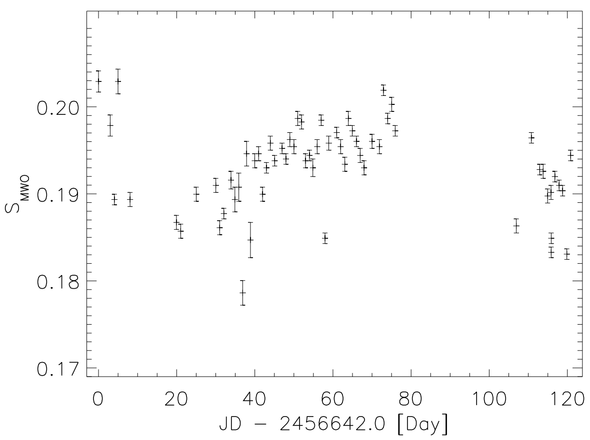

Fig. 12 S-index vs. time for τ Boo; from TIGRE spectra a transformation into the Mount-Wilson S-index scale has been derived. This S-index time series demonstrates the capability of TIGRE to produce densely sampled activity monitoring.

tions especially in the X-ray domain, which is also among the key science interests of the TIGRE PIs. To illustrate this point, we show in Fig. 11 a time series of He II λ4686 Å emission line profiles in the massive Oef supergiant λ Cep, recorded contemporaneously with an XMM-*Newton* X-ray observation of this star. The variability of the optical line revealed by our TIGRE spectra helps us constrain the properties of the structures in the stellar wind of λ Cep, thus providing crucial information for the interpretation of the simultaneously recorded X-ray spectra.

Finally we demonstrate TIGRE's monitoring capabilities, which may be both, dense and long-term. Figure 12 shows a dense coverage of the chromospheric variability of the S-index of the planet-hosting star τ Boo (cf. Butler et al. 1997). τ Boo is actually a binary consisting of an F6 dwarf and an M2 secondary; the hot Jupiter orbits around the A-component of τ Boo, which is a fairly active star, as indicated by its X-ray emission (Hünsch et al. 1999) and chromospheric activity (Baliunas et al. 1995). Donati et al. (2008) present evidence for polarity changes of the magnetic field of τ Boo on short time scales. The orbital period of the planet around τ Boo of 3.31 days may actually be synchronized with the stellar rotation period of 3.3 ± 0.5 days (see Baliunas et al. 1995). With individual TIGRE exposures of 5.5 min on a daily basis, short-term changes of the chromospheric emission become obvious.

5 Discussion

The conditions for observational astronomy have fundamentally changed over the last decades. Space-based observatories cover a substantial fraction of the electromagnetic spectrum and a number of 10 m class optical and infrared facilities have become available, mostly to North American and European astronomers. These "Big Science" facilities have become a vital and indispensable resource for modern astrophysics and must satisfy the needs of a large and diverse community in many different countries, in terms of instrumentation and allocation of observing time. Therefore, these facilities require huge investment in capital and usually substantial operating costs ensue. In fact, there is an enormous financial pressure on a number of 4 m class facilities, which are again expensive to run and are therefore frequently threatened by closure. These facilities must therefore also define their role and position to modern astrophysics.

Furthermore, the allocation of such precious resources typically occurs on a time scale of a year, thus making short-term program changes very difficult. On the other hand, monitoring programs, which need many years of observations for their completion, are hardly compatible with such a time allocation scheme. Consequently, it is a matter of debate to what extent the needs of modern astronomy can be fully served by big, versatile and public facilities. In fact, quite a number of important, recent discoveries in astrophysics, for example the discovery of extra-solar planets or dark energy, have been made by smaller, but dedicated instruments.

While the allocation of resources by consensus is most reasonable in general, it may still not be the best way of resource management; one might just imagine E. Hubble and O. Wilson argue in front of a time allocation committee to plead for their observations of yet another galaxy and yet another star .... At any rate, we firmly believe that visible science contributions can also be made with smaller but strongly focussed facilities. These are restricted in their instrumentation and are thus running very cost-efficiently. In this fashion science areas can be addressed, which fall outside the range covered by public facilities. Examples are the requirement of multi-wavelength coverage, close synchronization with space-based observations, or monitoring programs exploring the time domain on scales of months, years or even decades.

In addition to the low running cost, a dedicated facility like TIGRE is much easier to engage in riskier projects, objects of high interest can be fed into the system on very short notice, and we can easily provide support for space-based observations. And finally, the university institutes running TIGRE need to train students. By running our own programs with our own facilities, in addition to the use of remote public facilities, we can offer our students science projects where they are in charge themselves, enriching their hands-on experience and technical competence.

Given the whole situation described above, two strategic qualities of the concept of TIGRE have already proven their values: First of all, the autonomous, robotic operation of the telescope makes the observational work itself very cost-efficient and even independent on the quality of the internet connection. Data are stored locally and can, in principle, be downloaded any time later. Only a minimal outside control via the internet is required for reasons of safety of the valuable equipment. Second, the choice of a site within reach of a 30 min car drive from Guanajuato makes it possible to intervene even on relatively short notice. It greatly facilitates regular operations, which requires about two visits per week – one for routine maintenance, one typically to address special issues.

According to its private funding, TIGRE is not run as a public observatory. Nevertheless, the TIGRE team is open for scientific collaborations going beyond its member institutes. Any colleague with ideas well suited for the specific characteristics and strengths of TIGRE is invited to get in touch with us.

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