The Central Role of FORS1/2 Spectropolarimetric Observations for the Progress of Stellar Magnetism Studies

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The spectropolarimetric mode of the FOcal Reducer and low dispersion Spectrographs (FORS), which was first implemented in FORS1, and then moved to FORS2 seven years ago, has made it possible to probe the presence of magnetic fields in stars of different spectral classes at almost all stages of stellar evolution. While in the early days of FORS1, many of the observations were related to magnetic Ap/Bp stars and their progenitor Herbig Ae/Be stars, recent spectropolarimetric studies with FORS2 have involved more challenging targets, such as massive O- and B-type stars in clusters and in the field, very fast rotating massive stars with magnetospheres, Wolf–Rayet stars and central stars of planetary nebulae. The role of FORS observations for stellar magnetic field measurements is summarised and improvements in the measurement technique are described.

Magnetic fields in massive stars

During recent years a number of FORS2 magnetic studies have focused on the detection of magnetic fields in early B- and O-type stars. The characterisation of magnetic fields in massive stars is indispensable for the understanding of the conditions controlling the presence of those fields and their implications for stellar physical parameters and evolution. Accurate studies of the age, environment and kinematic characteristics of magnetic stars are also promising to gain new insights into the origin of these magnetic fields. While a number of early B-type stars were identified as magnetic several decades ago, the first magnetic field detection in an O-type star was achieved only 13 years ago, even though the existence of magnetic O-type stars had been suspected for a long time. The many unexplained phenomena observed in massive stars that are thought to be related to magnetic fields, like cyclical wind variability, Hα emission variation, chemical peculiarity, narrow X-ray emission lines and non-thermal radio/X-ray emission have all acted as indirect observational evidence for the presence of magnetic fields.

However direct measurements of the magnetic field strength in massive stars, using spectropolarimetry to determine the Zeeman splitting of the spectral lines are difficult, since only a few spectral lines are available for these measurements. In addition, these spectral lines are usually strongly broadened by rapid rotation and macroturbulence and frequently appear in emission or display P Cyg profiles. In high-resolution spectropolarimetric observations, broad spectral lines frequently extend over adjacent orders so that it is necessary to adopt order shapes to get the best continuum normalisation. Furthermore most of the existing high-resolution spectropolarimeters operate at smaller telescopes and cannot deliver the necessary high signal-to-noise (SNR) observations for the majority of the massive stars. In particular, O-type stars and Wolf–Rayet (WR) stars are rather faint. The Bright Star Catalog contains only about 50 O-type stars and very few WR stars.

Significant line broadening in massive stars appears to make the low-resolution VLT instrument FORS2 — and prior to that FORS1 — the most suitable instrument in the world to undertake the search for the presence of magnetic fields. FORS offers the appropriate spectral resolution and the required spectropolarimetric sensitivity, giving access to massive stars even in galaxies beyond the Milky Way. Only the Faint Object Camera and Spectrograph (FOCAS) at the Subaru Telescope has an operating spectropolarimetric mode and, pending the commissioning of the PEPSI spectrograph in polarimetric mode installed at the Large Binocular Telescope (LBT), no further high-resolution spectropolarimetric capabilities are available on any of the 8–10-metre-class telescopes.

We started the first spectropolarimetric observations of O-type stars with FORS1 in 2005. During a survey of thirteen O-type stars the discovery of the presence of a magnetic field was announced in the Of?p star HD 148937. The class of Of?p stars was introduced by Walborn (1973) and includes only five stars in our Galaxy. Of?p stars display recurrent spectral variations in certain spectral lines, sharp emission or P Cygni profiles in He I and the Balmer lines, and strong C III emission lines around 4650 Å. In recent years it has been shown that all Of?p stars are magnetic with field strengths from a few hundred Gauss to a few kG. Among them, only two Of?p stars, HD 148937 and CPD-28 2561, are observable from Paranal, and it is noteworthy that their first magnetic field detections were achieved through FORS1 and FORS2 observations (Hubrig et al., 2013).

All FORS1/2 observations of HD 148937 are presented in Figure 1, together with observations from the Echelle Spectro-Polarimetric Device for the Observation of Stars (ESPaDOnS), obtained at the Canada France Hawaii Telescope (CFHT) by Wade et al. (2012). This figure demonstrates the excellent agreement between the FORS2 and ESPaDOnS measurements, highlighting the outstanding potential of FORS2 for the detection of magnetic fields and the investigation of the magnetic field geometry in massive stars. Notably, while an exposure time of 21.5 hours at the CFHT was necessary to obtain seven binned measurements, the exposure time for the individual FORS2 observations accounted only for two to four minutes, and only 2.3 hours were used for our observations at six different epochs, including telescope presets and the usual overheads for readout time and retarder waveplate rotation.

Also our FORS2 measurements of the mean longitudinal magnetic field of the second Of?p star CPD-28 2561 were consistent with a single-wave variation during the stellar rotation cycle, indicating a dominant dipolar contribution to the magnetic field topology with an estimated polar strength of the surface dipole B_d

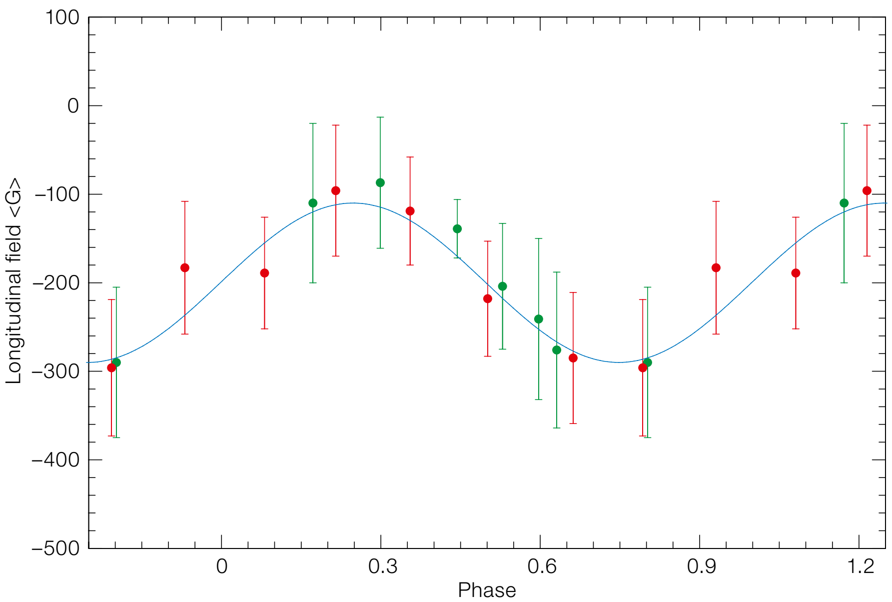

Figure 1. Longitudinal magnetic field variation of the Of?p star HD 148937 according to the 7.032-day period determined by Nazé et al. (2010). Red symbols correspond to ESPaDOnS observations (Wade et al., 2012) while green symbols are our FORS1 and FORS2 measurements (Hubrig et al., 2013). Note that the measurement errors for both ESPaDOnS and FORS1/2 observations are of similar order.

larger than 1.15 kG (Hubrig et al., 2015). We note that in our studies of these two Of?p stars, none of the reported detections reached a 4σ significance level. While 3σ detections with FORS2 cannot always be trusted for single observations, they are genuine if the measurements show smooth variations over the rotation period, similar to those found for the Of?p stars HD 148937 and CPD-28 2561.

The presence of magnetic fields might change our whole picture about the evolution from O stars via WR stars to supernovae or gamma-ray bursts. Neglecting magnetic fields could be one of the reasons why models and observations of massive-star populations are still in conflict. Magnetic fields in massive stars may also be important in studies of the dynamics of the stellar winds. A few years ago, our team carried out FORS2 observations of a sample of Galactic WR stars and one WR star in the Large Magellanic Cloud. Magnetic fields in WR stars are especially hard to detect because of wind broadening of their spectral lines. Moreover all photospheric lines are absent and the magnetic field is measured on emission lines formed in the strong wind. Remarkably spectropolarimetric monitoring of WR6, one of the brightest WR stars, revealed the sinusoidal nature of $\langle B_z \rangle$ variations with a period of 3.77 days and an amplitude of only 70–90 G (Hubrig et al., 2016).

Pulsating stars

Recent high-precision, uninterrupted high-cadence, space photometry using a number of satellites (e.g., the Wide Field Infrared Explorer [WIRE], the Microvariability and Oscillation of Stars [MOST], the Convection Rotation et Transits planétaires [CoRoT], Kepler and the Bright Target Exploter [BRITE]) have led to a revolutionary change in the observational evaluation of variability of massive stars. Supported by results from photometric monitoring, it is expected that a large fraction of massive stars show photometric variability, due to either β Cephei- or slowly pulsating B-type star (SPB) like pulsations, stochastic *p*-modes or convectively-driven internal gravity waves.

High-resolution spectropolarimetric observations of pulsating stars frequently fail to show credible measurement results if the whole sequence of sub-exposures at different retarder waveplate angles has a duration comparable to the timescale of the pulsation variability. As an example, even for the bright, fourth magnitude β Cep star ξ^1 CMa with a pulsation period of 5 hours, a full High Accuracy Radial Velocity Planetary Searcher (HARPS) sequence of sub-exposures requires about 30 minutes. In contrast one FORS2 observation of the same star lasts less than 10 minutes. Owing to the strong changes in the line profile positions and profile shape in the spectra of pulsating stars, a method using spectra averaged over all sub-exposures leads to erroneous wavelength shifts, and thus to wrong values for the longitudinal magnetic field.

For the first time, FORS1 magnetic field surveys of SPB stars and β Cep stars were carried out by our team from 2003 to 2008. As a number of pulsating stars showed the presence of a magnetic field, our observations implied that β Cep and SPB stars can no longer be considered as classes of non-magnetic pulsators. Notably, although the presence of magnetic fields in these stars has already been known for more than ten years, the effect of these fields on the oscillation properties is not yet understood and remains to be studied.

ξ^1 CMa, discovered as magnetic with FORS1 observations, is still the record holder with the strongest mean longitudinal magnetic field among the β Cep stars of the order of 300–400 G (Hubrig et al., 2006). Using FORS2 measurements obtained in Service Mode in 2009/10, we were able to detect rotational modulation of its magnetic field with a period of about 2.19 days and estimate a magnetic dipole strength of about 5.3 kG (Hubrig et al., 2011a).

Fully unexpected observations of this particular star with the XMM-Newton telescope revealed, for the first time, X-ray pulsations with the same period as the stellar radial pulsation (Oskinova et al., 2014). This first discovery of X-ray pulsations from a non-degenerate massive star stimulates theoretical considerations for the physical processes operating in magnetised stellar winds.

Our observations of pulsating stars also allowed the first detection of a magnetic field in another β Cep star, ε Lupi, which is a double-lined spectroscopic binary system and which recently received

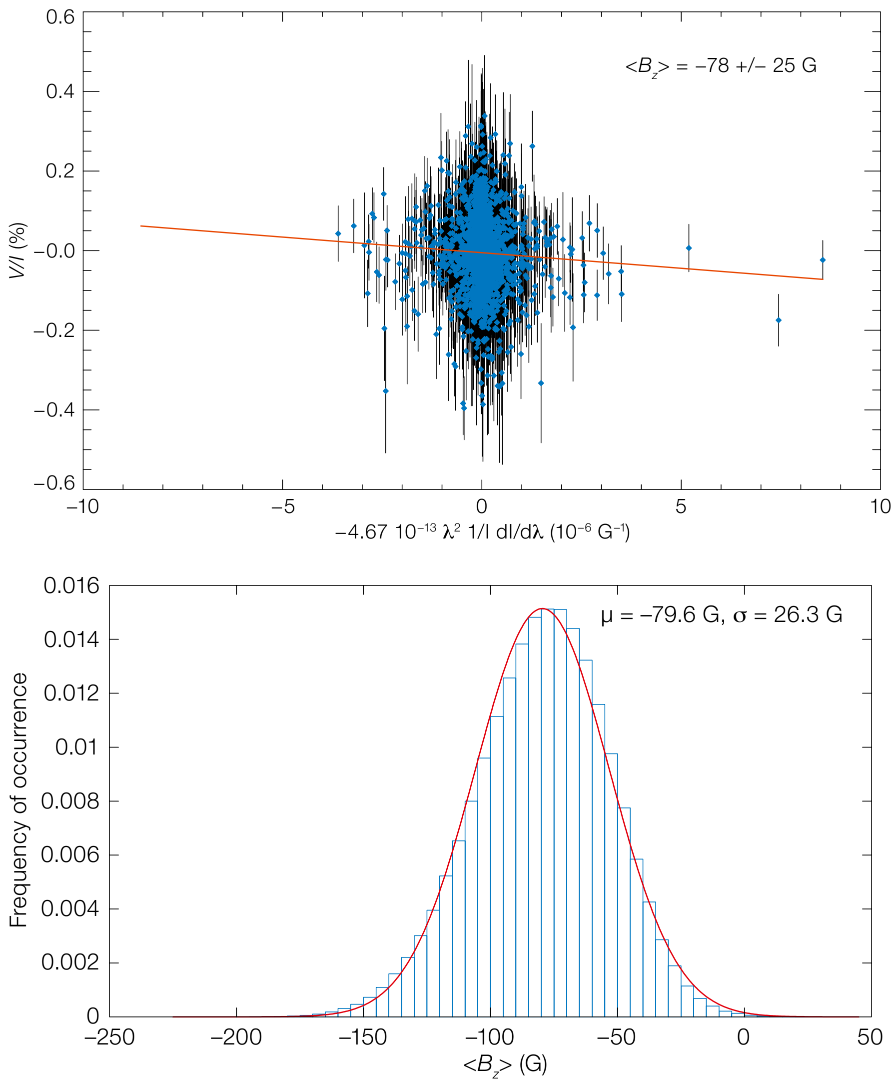

Figure 2. Hen 2-113: Monte Carlo bootstrapping regression detection of a $\langle B_z \rangle$ = −80 +/− 26 G mean longitudinal magnetic field using uncontaminated stellar lines only (upper) and the corresponding (slightly non-Gaussian) distribution of $\langle B_z \rangle$ obtained from the Monte-Carlo bootstrapping technique (lower).

attention due to the presence of a magnetic field in both components. Since binary systems with magnetic components are rather rare, the detection of a magnetic field in this system using low resolution FORS1 spectropolarimetry indicates the potential of FORS2 for magnetic field searches in binary or multiple systems.

Diverse exotic targets

The spectropolarimetric capability of the FORSes has also been exploited by observations of a number of stars with a specific circumstellar environment, such as: the central stars of planetary nebulae (PNe) with different morphologies, including round, elliptical and bipolar; PNe central stars of WR type; Herbig Ae/Be stars with circumstellar discs showing magnetospheric accretion; and the X-ray binary Cyg X-1 containing a black hole.

First reports on magnetic fields in PNe using FORS1 measurements and claiming the detection of strong magnetic fields in two central stars could not be confirmed by improved analysis methods (Jordan et al., 2012). New FORS2 spectropolarimetric observations of a sample of 12 PN central stars achieved much lower detection limits than previous observations (Steffen et al., 2014). Our measurements have excluded the presence of a strong magnetic field in any of the central stars of our sample. However weaker fields of the order of 100 G were detected in the central star of the young elliptical planetary nebula IC 418 as well as in the WR-type central star of the bipolar nebula Hen 2-113.

We chose a subset of spectral lines originating exclusively in the photosphere and the wind of the central stars and not appearing in the surrounding nebular spectra for the measurements. Furthermore the pipeline for the spectral extraction includes by default background subtraction. In Figure 2 we present the Monte Carlo bootstrapping regression detection of a $\langle B_z \rangle$ = −80 +/− 26 G mean longitudinal magnetic field in Hen 2-113 using uncontaminated stellar lines only. Since the majority of the central stars of planetary nebulae are very faint, only low-resolution FORS2 observations allow the detected magnetic fields of the central stars to be monitored with sufficient precision.

The first FORS1 observations of Herbig Ae/Be stars by our team date back to 2003. Models of magnetically driven accretion and outflows are not well developed for these stars due to poor knowledge of their magnetic field topology. On the other hand it is obvious that understanding the interaction between the central stars, their magnetic fields and their protoplanetary discs is crucial to our efforts to account for the diversity of exoplanetary systems. Only about 20 Herbig stars have been reported to host magnetic fields so far and our recent compilation of stars with published measurements of magnetic fields indicates that their field strength is predominantly below 200 G.

Among the sample of Herbig Ae/Be stars HD 101412 stands out due to its very slow rotation and the presence of chemical spots. Wade et al. (2007) measured a magnetic field of the order of +500 G using hydrogen lines and −500 G using metal lines with FORS1 from the same spectra. A subsequent study of Ultraviolet Visible EchelleSpectrograph (UVES) and HARPS spectra of HD 101412

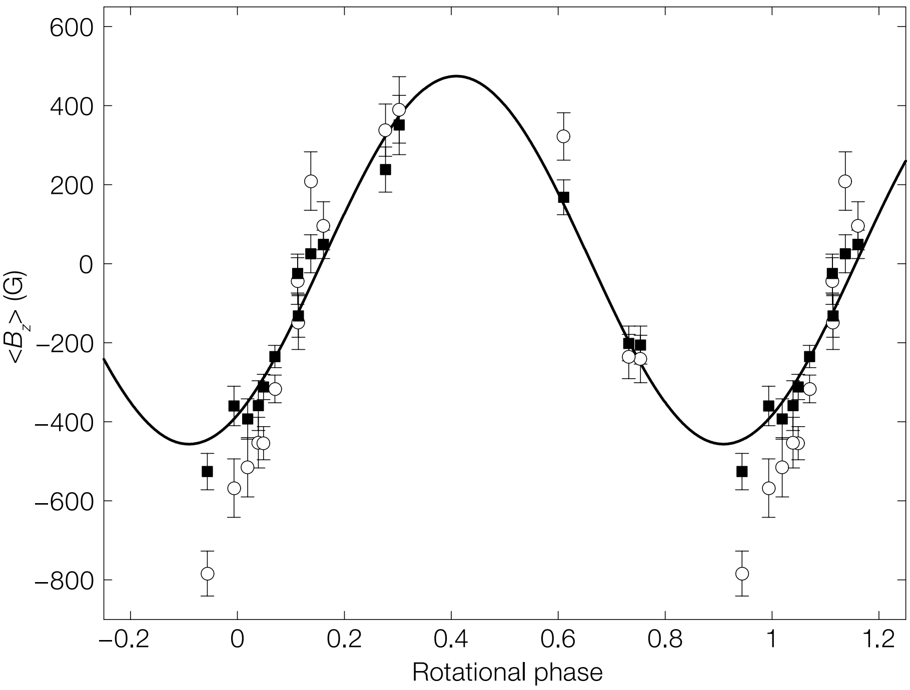

Figure 3. Phase diagram of HD 101412 with the best sinusoidal fit for the longitudinal magnetic field measurements using all lines (filled squares) and hydrogen lines only (open circles).

revealed the presence of resolved, magnetically split, lines, indicating a variable magnetic field modulus changing from 2.5 to 3.5 kG (Hubrig et al., 2010). Our multi-epoch FORS2 polarimetric spectra of this star, acquired over 62 days in Service Mode in 2010, have been used to search for a rotation period and to constrain the geometry of the magnetic field. The search for the rotation period using magnetic and photometric data resulted in P = 42.076 +/– 0.017 days (Hubrig et al., 2011b). In Figure 3 we present the corresponding phase diagram for all the available FORS2 mean longitudinal magnetic field measurements using either the whole spectrum or only the hydrogen lines, including the best sinusoidal fit to these data. The presence of a rather strong magnetic field on the surface of HD 101412 makes it one of the best candidates for studies of the impact of the magnetic field on the physical processes occurring during stellar formation.

Cyg X-1 is one of the brightest X-ray binary systems with an orbital period of 5.6 days. This system consists of an optical component — an O9.7Iab supergiant — and a black hole as an invisible component. Previous spectropolarimetric observations with FORS1 revealed the presence of a weak longitudinal magnetic field in the optical component (Karitskaya et al., 2010). The detected magnetic field showed variations over the orbital period of 5.6 days with an amplitude of about 100 G. This was the first successful attempt to measure a magnetic field in a binary with a black hole. However the character of the variability of the magnetic field has changed between the different years of observations, suggesting the existence of year-to-year variations. Quasi-simultaneous FORS2 monitoring of circular and linear polarisation over the orbital period is scheduled in observing Period 97. Such monitoring will provide us with unique information about the magnetic field topology and the processes taking place in a system containing a black hole.

Improvements in measurement technique

Since our last *Messenger* report on FORS1 observations (Hubrig et al., 2009), the measurement strategy has been modified in several aspects. The parallel and perpendicular beams are extracted from the raw FORS2 data using a pipeline written in the MIDAS environment by Thomas Szeifert, who was the first person to recognise the potential of FORS1 for surveying magnetic fields in stellar atmospheres, and he has supplied our team with the necessary knowhow. In the reduction process we perform a rectification of the Stokes V/I spectra and calculate null profiles, N, as pairwise differences from all available V profiles. From these profiles, 3σ-outliers are identified and used to clip the V profiles. This step removes spurious signals, which mostly come from cosmic rays, and also reduces the noise. A full description of the updated data reduction and analysis will be presented in a paper by Schöller et al. (in prep.).

The mean longitudinal magnetic field, $\langle B_z \rangle$, is defined by the slope of the weighted linear regression line through the measured data points, where the weight of each data point is given by the squared signal-to-noise ratio of the Stokes V spectrum. The formal 1σ error of $\langle B_z \rangle$ is obtained from the standard relations for weighted linear regression. This error is inversely proportional to the root mean square (RMS) signal-to-noise ratio of Stokes V. Finally we apply the factor $\sqrt{(\chi^2_{min}/\nu)}$ to the error determined from the linear regression if larger than 1.

Since 2014 we have also implemented the Monte-Carlo bootstrapping technique, where we typically generate M = 250 000 statistical variations of the original dataset and analyse the resulting distribution $P(\langle B_z \rangle)$ of the M regression results. The mean and standard deviation of this distribution are identified with the most likely mean longitudinal magnetic field and its 1σ error respectively. The main advantage of this method is that it provides an independent error estimate.

A number of discrepancies in the published measurement accuracies have been reported by Bagnulo et al. (2015a; see also Bagnulo et al., 2015b), who used the FORS1 pipeline to reduce the full content of the FORS1 archive. The same authors have published a few similar papers in recent years suggesting that very small amounts of instrument flexure, negligible in most of the instrument applications, may be responsible for some spurious magnetic field detections and that FORS1 detections may be considered reliable only at a level greater than 5σ. However no report on the presence of flexure from any astronomer observing with the FORS instruments has ever been published in the past. The authors also discuss the impact of seeing if the exposure time is comparable with the atmospheric coherence time (which they incorrectly assume to be in seconds and not in milliseconds). Not until their most recent work have these authors presented the level of intensity flux for each spectrum and reported which spectral regions were used for the magnetic field measurements. However no fluxes for left-hand and right-hand polarised spectra are available separately, thus it is not possible to reproduce their measurements. We note that small changes in the spectral regions selected for the measurements can also have a significant impact on the measurement results.

Since the measurement accuracies predominantly depend on photon noise, an improper extraction of the spectra, for instance the use of smaller extraction windows, would explain why Bagnulo et al. disregarded 3σ detections by other authors. If the levels of flux for each subexposure compiled in the catalogue of Bagnulo et al. (2015a) are inspected, it shows that their levels are frequently lower, down to 70%, in comparison with those obtained in our studies. It is obvious that the detection of weak magnetic fields is particularly affected if the extracted fluxes are low. From the consideration of the signal-to-noise ratios presented by Bagnulo et al., we also noted that emission lines are not taken into account during the measurements. The reason for this is not clear as there is no need to differentiate between absorption and emission lines: the applied relation between the Stokes *V* signal and the slope of the spectral line wing holds for both types of lines, so that the signals of emission and absorption lines add rather than cancel.

In order to increase the reliability of FORS2 magnetic field detections, but also to carry out a quantitative atmospheric analysis and probe spectral variability, it is certainly helpful to follow up FORS2 detections with high-resolution HARPS observations. To our knowledge the only collaboration that uses FORS2 and HARPS to monitor magnetic fields is the BOB (B-fields in OB stars) collaboration (Morel et al., 2014), which is focused on the search for magnetic fields in massive stars. Combining observations with different instruments has allowed the BOB collaboration to report the presence of magnetic fields in a number of massive stars during the last couple of years. As an example, the first detection of a magnetic field in the single slowly rotating O9.7V star HD 54879 was achieved with FORS2 and was followed up with HARPS observations. These observations show that HD 54879 is so far the strongest magnetic single O-type star detected with a stable and normal optical spectrum (Castro et al., 2015).

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Star trails at Paranal over three of the Auxiliary Telescopes of the Very Large Telescope Interferometer (VLTI).