

Beyond Phase 3: The FORS1 Catalogue of Stellar Magnetic Fields

Stefano Bagnulo¹
John D. Landstreet^{1,2}
Luca Fossati³

¹ Armagh Observatory, College Hill,
Armagh, United Kingdom

² University of Western Ontario, London,
Canada

³ Space Research Institute, Austrian
Academy of Sciences, Graz, Austria

Over the course of a decade of operations, more than 200 nights of telescope time have been granted for magnetic field measurements with the FORS1 instrument on the VLT. Motivated by some conflicting results published in the literature, we have studied the instrument characteristics and critically revised previous magnetic field detections obtained with FORS1. Our study has led to the publication of a catalogue of 1400 magnetic field measurements of a sample of 850 different stars, together with their intensity spectra. This catalogue includes nearly all the circular spectropolarimetric measurements taken during ten years of operation. Here we summarise some of the lessons learned from the analysis of the FORS1 stellar spectropolarimetric archive.

The twin Focal Reducer and low dispersion Spectrograph FORS1/2 instruments (Appenzeller et al., 1998), operated at the Paranal Observatory, have been one of the great success stories of the Very Large Telescope (VLT) instrumentation. These two instruments are versatile tools for observing faint objects, primarily with direct imaging and low-resolution multi-object spectroscopy over the full optical band. FORS1 was in use from 1999 until 2009; FORS2 is still in regular use. In addition to its imaging and spectroscopic capabilities, FORS1 was equipped with polarimetric optics, and when FORS1 was retired, its polarisation optics system was moved to FORS2 and is still available.

The FORS polarimeters were originally intended for observations of rather faint objects. Examples are: broadband and emission-line linear polarisation spectra of pre-main sequence Herbig Ae and Be stars and faint classical Be stars; meas-

urement of the interstellar polarisation of extragalactic stars; intrinsic polarisation of the nuclei of Seyfert galaxies and AM Herculis white dwarfs; and circular spectropolarimetry of line and continuum radiation of magnetic white dwarfs with fields of hundreds of Tesla (100 Tesla = 1 megaGauss, MG) or more. However, it turned out that a non-negligible fraction of FORS1 time was used instead to measure relatively weak fields of bright stars.

Measuring magnetic fields with FORS

Magnetic field measurements with FORS are possible mainly as a consequence of the physics of the Zeeman effect. A spectral line formed in a stellar atmosphere permeated with a strong magnetic field splits into numerous components, one group (π components) centred on the wavelength of the unsplit line, and two other line groups (σ components) shifted to shorter and longer wavelengths around the π components. In a white dwarf with a field of some MG, this splitting is clearly visible in the normal intensity profiles of the common H Balmer lines, and provides a measure of the mean magnetic field strength $\langle |B| \rangle$ averaged over the visible stellar hemisphere. In addition, if the field has a large line-of-sight component, the groups of σ components are circularly polarised in opposite senses.

On account of this combination of line splitting and polarisation, the mean wavelength of the spectral line of a magnetic star, as seen in right circularly polarised light, will be at a slightly different wavelength from that of the same line seen in left circularly polarised light. This wavelength difference is proportional to the mean line-of-sight component of the field $\langle B_z \rangle$, averaged over the visible stellar hemisphere. If the difference between the two line profiles is measured, there will be net circular polarisation of one sign in one wing of the average line, and of the other sign in the other wing. Thus an observational signature of a magnetic field is net circular polarisation in the wings of a spectral line, correlated with the sign of the slope of the line.

With FORS, measurements of this kind were expected to detect even rather weak fields of a few kG using the very broad

Balmer lines of white dwarfs, and in fact such weak fields have been detected (e.g., Aznar Cuadrado et al., 2004). It was not obvious that FORS1 could be used to measure the weaker (hundreds of G) magnetic fields of upper main sequence stars, as such measurements are mainly carried out using sharp metal lines with spectropolarimeters of much higher resolving power than that of FORS. However, an experiment carried out in 2001 to try to measure the kG magnetic field of the known magnetic “peculiar A” (Ap star) HD 94660 revealed that not only is the field of this star readily detectable using the star’s Balmer lines, but that it is also easily measured using the metal line spectrum (Bagnulo et al., 2002). This was a very surprising result. Since almost all the spectral lines are blended, it was expected that the polarisation signature in metal lines would largely cancel out, but in fact the circular polarisation remains closely connected with the local line slope, and magnetic fields are easily detectable.

The principle of magnetic field measurements is summarised in Figure 1. In the upper panel, the black solid line shows the uncorrected detected intensity profile. The red solid line is the reduced Stokes V profile ($P_V = V/I$) in % units. Photon noise error bars are centred on -0.5% and appear as a light blue background, on which the null profile (also offset by -0.5% for display purposes) is superposed (blue solid line). The null profile is an experimental estimate of the error, and should be scattered around zero with the same full width at half maximum (FWHM) as the light blue error bars. Spectral regions, highlighted by green bars above and below the spectra, have been used to determine the $\langle B_z \rangle$ value from H Balmer lines, and the magenta bars highlight the spectral regions used to estimate the magnetic field from metal lines.

The four bottom panels of Figure 1 show the best-fit, obtained by fitting with a straight line, P_V as a function of the quantity $\propto \lambda^2(1/l) (dl/d\lambda)$; where $l(\lambda)$ is the intensity spectrum. The slope of the fitting line is proportional to the mean longitudinal magnetic field. For quality check purposes, the magnetic field $\langle N_z \rangle$ is also measured from the null profile, and is expected to be zero within the error bars.

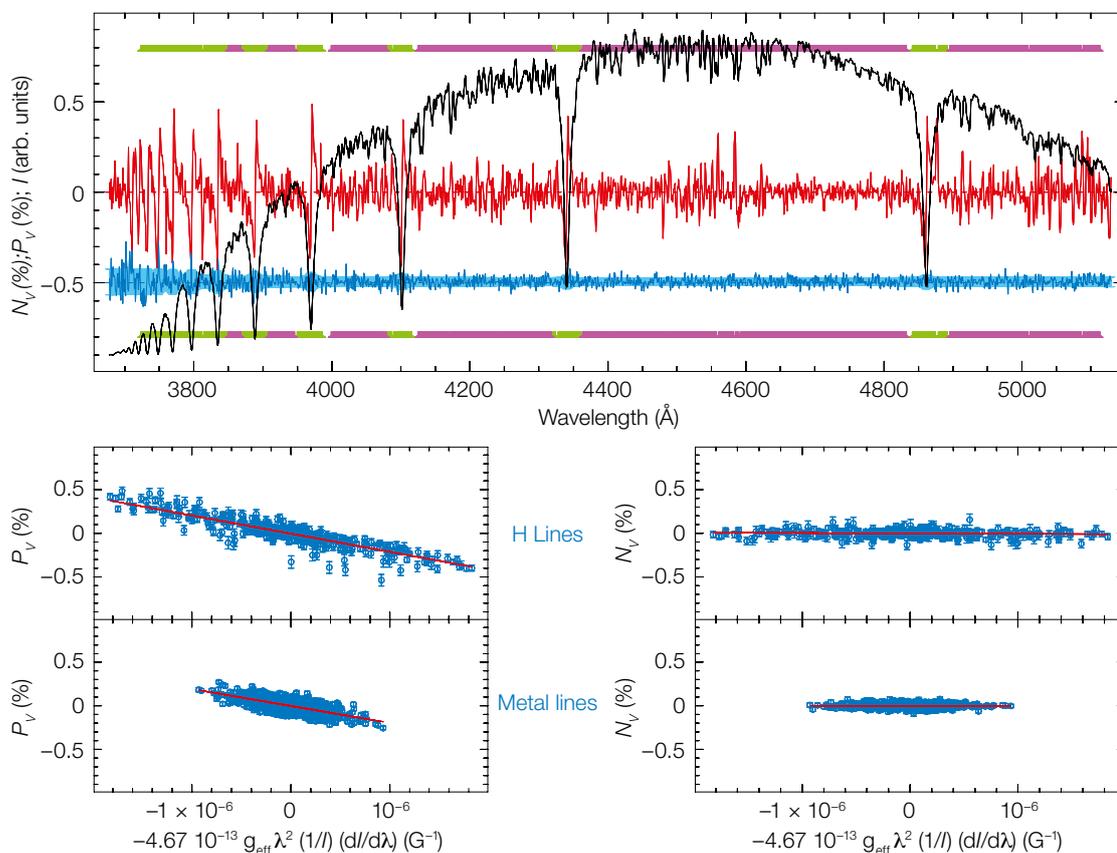


Figure 1. An example of FORS magnetic field measurements: the case of the Ap star HD 94660. The upper plot shows the intensity and Stokes V profiles and the four lower panels show the straight line best fits for P_V . See text for more details.

In this example the field values ($\langle B_z \rangle \sim -2000$ G and $\langle N_z \rangle \sim 0$ G) are determined with a formal precision of ~ 40 G for Balmer lines and ~ 25 G for metal lines, i.e., with an error bar even smaller than from H Balmer lines! With this result, it became clear that FORS1 could be used for measuring magnetic fields in main sequence stars and a large new parameter space for the study of stellar magnetic fields was opened up to investigation with this instrument.

Searching for magnetic fields with FORS

The possibility of using a spectropolarimeter on an 8-metre telescope to observe magnetic fields in stars other than white dwarfs very quickly led to surveys of various kinds of stars little studied before. Wade et al. (2005; 2007) carried out an extensive search for magnetism in pre-main sequence Herbig Ae stars, and discovered a field in the southern star HD 101412, although only at about the 5σ significance level in a single observation. Bagnulo et al. (2006) used

FORS in multi-object mode to search for magnetic fields among magnetic Ap stars (already known to have fairly strong fields) in open clusters. Since stellar ages can be precisely determined from cluster ages, it was possible to use these data to demonstrate that Ap magnetic fields decline strongly with time on the main sequence (Landstreet et al., 2008). A similar investigation, but on field stars, was started by Hubrig et al. (2006).

Hubrig, Schoeller and their collaborators started a number of surveys of Herbig stars, HgMn and PGa stars (the hotter extension of the HgMn stars, with rich P II, Mn II, Ga II and Hg II spectra), pulsating B stars, normal B stars, classical Be stars, and O-type stars (see Hubrig et al. [2009] and references therein). They reported the discovery that magnetic fields are often present in all these kinds of stars. Other programmes focused on compact stars, such as hot subdwarfs (O’Toole et al., 2005) and central stars of planetary nebulae (Jordan et al., 2005), with reports that both these categories of stars are often magnetic.

Not long after a number of magnetic field measurement programmes were started and carried out on FORS1, the Echelle Spectropolarimetric Device for the Observations of Stars (ESPaDONs) high-resolution spectropolarimeter was commissioned on the Canada–France–Hawaii Telescope. When results from the two polarimeters were compared, it became clear that a number of field discoveries reported for a wide variety of stellar types, often on the basis of one or two FORS detections at the 3σ to 5σ level, were not consistent with the non-detections, sometimes with substantially smaller uncertainties, obtained with ESPaDONs (Silvester et al., 2009; Aurière et al., 2010; Shultz et al., 2012). This led us to become concerned by the possibility that FORS data were not being correctly interpreted, and/or that there were subtle problems with FORS in spectropolarimetric mode that had not been identified by observers.

As a result, we started a large project aimed at fully understanding the situation. This began with a basic paper describing

in detail the theory of data reduction in two-beam spectropolarimeters with beam-swapping (Bagnulo et al., 2009). Then we created routines for automatic frame classification and data reduction (particularly with the help of the late ESO software developer, Carlo Izzo). The new suite of programmes (partially based on the ESO FORS pipeline, see Izzo et al. [2010]) was then used to completely re-analyse almost all the magnetic field measurements made with FORS1, in a homogeneous way.

During data reduction, a number of choices have to be made (for example, about how to best deal with spectrum extraction, with cosmic rays, etc.). Use of different reduction algorithms may have small but non-negligible effects on the final measurements, but it is not always obvious how to distinguish a better from a worse choice. Our software tool allowed us to study the effects of various algorithms on a large data sample, sometimes only to conclude that it is not possible to identify the optimal reduction choices, and that the small ambiguities introduced by the data reduction should be considered as additional noise to the final measurement. Most importantly, our analysis of the full dataset allowed us to firmly conclude that the accuracy, claimed for certain measurements, placed demands on FORS1 stability that were probably not realistic, and may well be very difficult for any Cassegrain instrument to meet.

Non-photon noise

While it is very natural to predict that instrument flexure can have a negative impact on the accuracy of a measurement, perhaps it is not so obvious to understand exactly how and why instrument flexure may be responsible for a spurious polarisation signal in a spectral line. In order to understand this, it is necessary to remember that polarimetry is a differential technique, i.e., by definition, both linear and circular polarisations are measured through the difference of two signals. In particular, Stokes V is given by the difference between right- and left-hand circular polarisation (RHP and LHP, respectively). In the case of FORS, the RHP and LHP signals are

obtained by introducing a $\lambda/4$ retarder waveplate and a Wollaston prism into the optical path. A grism (and perhaps an order separator filter) are then introduced in the optical train to perform spectral analysis, and finally a CCD records the intensity of two spectra originally circularly polarised in opposite directions. If the original signal is non-polarised, then after perfectly accurate flatfielding and wavelength calibration, the two spectra are identical, and their difference is only due to noise. If the spectral line is polarised (for instance due to the Zeeman effect), then its LHP and RHP spectra appear slightly offset, and their difference is a non-zero Stokes V spectrum.

The LHP and RHP spectra could be offset as a result of any tiny imperfection in the wavelength calibration. By applying the beam-swapping technique, the LHP and RHP spectra exchange their position in the optical path (this is possible with a simple 90° rotation of the $\lambda/4$ waveplate between subsequent measurements). In this way, most instrumental features cancel out even without the use of calibrations. Beam-swapping can cure some systematic offsets between the beams, e.g., when both RHP and LHP are offset by the same amount after the retarder waveplate rotates, or when there is a systematic offset between RHP and LHP that remains constant as the retarder waveplate rotates. However, it cannot compensate for a differential offset between the RHP and LHP spectra as the retarder waveplate rotates. Some simple numerical simulations (see Bagnulo et al., 2009 and 2013) show that an offset of this kind as small as 1/100 of the FWHM of a spectral line may create a detectable spurious polarisation signal.

In many cases, with FORS, spectral lines are sampled with a few pixels at most, hence a differential flexure of the order of a small fraction of a pixel may produce a spurious signal. It is not always possible to avoid such small amounts of flexure in a Cassegrain mounted instrument, and the occurrence of spurious spikes in the Stokes V spectra is more likely in narrower than in broader lines. Spurious signals due to flexure may sometimes be distinguished from Zeeman signatures by taking into account that the wavelength-integrated Stokes V profile due to Zeeman

effect is zero: therefore a spike in Stokes V that does not obey this rule is likely to be ascribed to flexure.

Instrument flexure is not the only possible source of spurious signals: variations in guiding or even seeing effects may cause the same effect if combined with a less-than-perfect relative wavelength calibration of the RHP and LHP (for details see Bagnulo et al., 2013).

The revised incidence of magnetic fields in various classes of stars

Full data reduction carried out with our suite of programs allowed us to test whether the numerous but controversial detections of apparently significant magnetic fields in a wide variety of stars were robustly reproduced using the best reduction choices identified by our experiments. One of our findings was that uncertainties may be of the order of 30% larger than that expected from photon-counting statistics alone. Our work showed that most of the detections reported on the basis of single $3-5\sigma$ field measurements were spurious (Bagnulo et al., 2012). Some FORS1 field discoveries, usually those at a higher significance level, were confirmed, for example those in the white dwarfs WD0446-789 and WD2359-434 and in the β Cep star ξ^1 CMa. However, the reports that large fractions of pulsating B stars, classical Be stars, normal B stars, O stars, and HgMn peculiar B stars possess weak magnetic fields, as claimed in the articles cited by Hubrig et al. (2009), were generally not confirmed. The discovery that about half of the Herbig Ae/Be stars possess a magnetic field was also not confirmed (Wade et al. [2007] had suggested an occurrence of $\sim 10\%$, consistent with that for main sequence A and B stars). Similarly, we could not confirm any of the field detections in hot subdwarfs and central stars of planetary nebulae — null results were then reported in detail by Leone et al. (2011), Jordan et al. (2012) and Landstreet et al. (2012).

Study of these spurious results, and also the systematic examination of the fairly large body of magnetic field measurements carried out on magnetic Ap stars, allowed us to obtain a clearer

understanding of the strengths and limitations of FORS for measuring weak magnetic fields. In general we found that FORS measurements of a single star are internally consistent at approximately the level expected from the uncertainties derived with our reduction programmes (Landstreet et al., 2014). However, there are occasional measurements that deviate from the expected behaviour by a few σ . We call these inconsistent measures occasional outliers, and find that they seem to occur in a few percent of measurements. Thus field discoveries based on single measurements significant at the 4–5 σ level cannot be considered as definite detections.

A public catalogue of FORS1 magnetic field measurements

As a final outcome of our study of the FORS1 archive, we have published a nearly complete catalogue of re-reduced FORS1 magnetic field measurements (Bagnulo et al., 2015). The FORS1 archive includes about 1400 observing series, for a total of more than about 12 000 scientific frames, obtained within the context of almost 60 observing programmes, using more than 2000 hours of telescope time and about 340 hours of shutter open time. The content of our catalogue is available at Catalogue de Donées Stellaire (CDS¹) and Bagnulo et al. (2015) includes an abridged version in the form of a printable table.

This catalogue is not the definitive, ultimate reduction of the FORS1 magnetic dataset however. As discussed in all our earlier papers, several different choices made during data reduction are equally reasonable, but lead to somewhat different results. However, the reductions leading to our catalogue are based on reasonable choices applied in a consistent way to all the FORS1 field measurements. In this respect our catalogue offers a more homogeneous overview than a simple collection of the same measurements in the literature. Our catalogue may be used also for a number of statistical studies, many of them presented in detail by Bagnulo et al. (2012; 2015) and Landstreet et al. (2014).

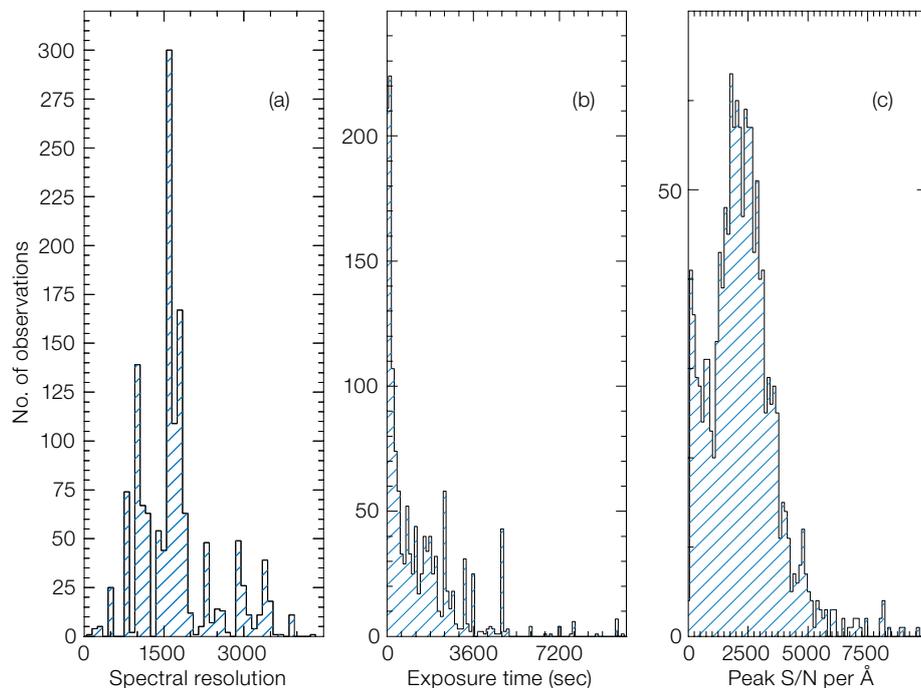


Figure 2 shows three histograms that we have built using data extracted from the FORS1 archive: the distribution of the adopted spectral resolution, the distribution of the exposure time, and the distribution of the peak signal-to-noise reached after an observing series. Looking at this figure, a number of very interesting features are apparent. Panel (a) shows that users wanted to have the highest possible resolution (in fact, magnetic fields are probably best measured at a higher resolution than offered by the FORS grisms), even at the expense of dramatic light losses, as spectral resolution > 1000–1500 could be obtained only by setting the slit width to sub-arcsecond values. On the other hand, panel (b) tells us that light losses were probably not so much of an issue: many observations were carried out with just a few seconds of shutter time, clearly on very bright targets. The high overhead of such short exposures is the main reason for the large discrepancy between assigned telescope time and shutter time. In effect, many programmes were carried out on FORS1 not because it was on an 8-metre telescope, but because it was the only spectropolarimeter available at ESO at the time (see Bagnulo et al., 2012).

Panel (c) shows the distribution of the peak signal-to-noise ratio (S/N) of the

Figure 2. Some statistical data from the analysis of the FORS1 archive of circular spectropolarimetric data. Figure 2a shows the spectral resolution deduced from the analysis of arc lines. The histograms in Figures 2b (shutter time) and 2c (S/N) refer to an observing series (typically composed of eight individual exposures).

observing series used for field measurements. It is interesting to note that even with an 8-metre telescope and with very bright stars, photon noise cannot be pushed down arbitrarily far, due to the CCD saturation limit and the non-negligible amount of CCD readout overheads. The typical maximum electron counts that one can reach in a FORS frame in a 1 Å spectral bin without saturation is generally < 10⁶ (the exact figure depends on the grism dispersion and on seeing), and the typical maximum S/N that can be achieved with a series of eight exposures is 2000–3000. Depending on the spectral type of the star, this corresponds to an error bar of a few tens of Gauss.

The relationship between peak S/N and error bar is shown in Figure 3, which shows that the highest precision that can be achieved, without ridiculously long overheads for CCD readout, is of the order of tens of Gauss (remember that to improve the detection threshold by a factor of two one would need four times the number of exposures). In conclusion,

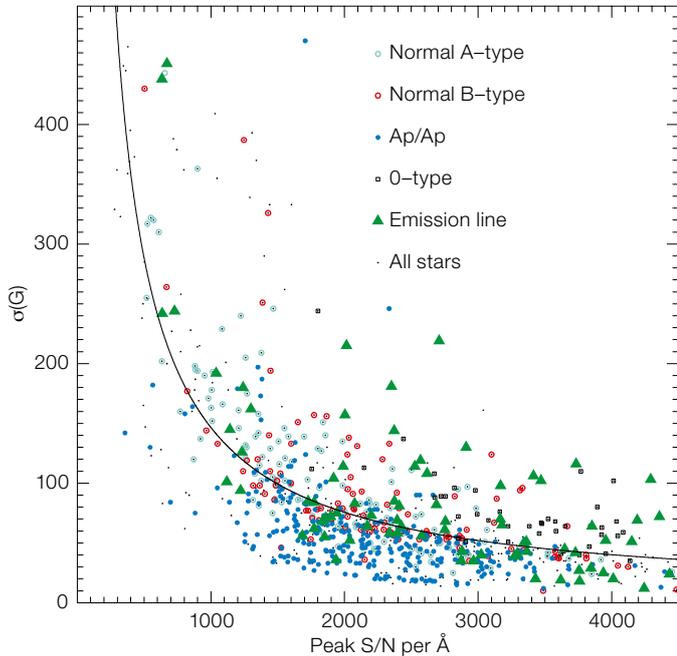


Figure 3. The error bar $\sigma(G)$ from the analysis of all spectral lines as a function of the peak S/N per \AA for various kinds of stars.

satellite and powerful instrument for magnetic field measurements. It is also suitable for projects where enough time is allocated so that initial field discoveries at the few σ level can be confirmed by repeated measurements.

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Links

- ¹ FORS1 polarimetric star catalogue: <http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/583/A115>
² FORS2 Exposure Time Calculator: <http://www.eso.org/observing/etc/bin/gen/form?INS.NAME=FORS+INS.MODE=spectro>

even if the error bars were determined only by photon noise, FORS could not achieve the same precision reached with high resolution spectropolarimeters such as ESPaDOnS and HARPSpol.

Complemented by the FORS Exposure Time Calculator², Figure 3 may be used as a tool for planning measurements of magnetic fields with FORS2. More details are given in Bagnulo et al. (2015).

In terms of field measurement accuracy, FORS cannot compete with a high resolution spectropolarimeter sitting on a thermally and mechanically isolated bench (like ESPaDOnS and HARPSpol) and is not the optimal instrument to search for very weak fields (≤ 100 – 200 G) in bright stars. However, when used with faint objects known or expected to have fields detectable at the several σ level (in particular in objects with broad spectral lines), FORS is an extremely ver-

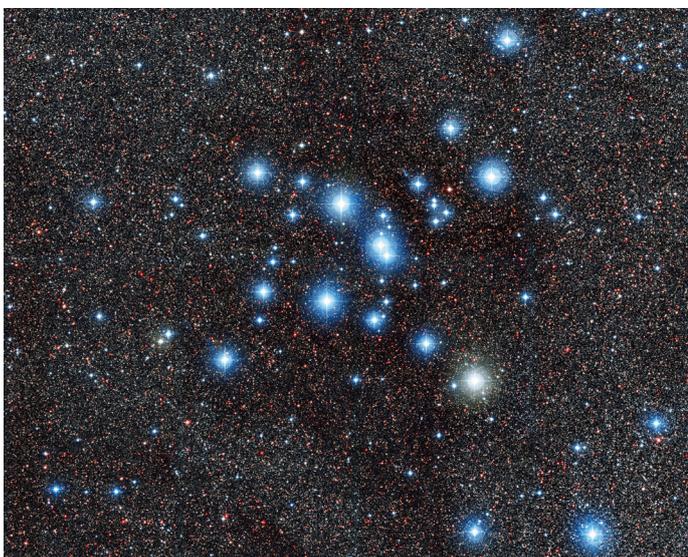


Image of the open cluster NGC 6745 (M7) obtained with the Wide Field Imager (WFI) on the MPG/ESO 2.2-metre telescope. *B*, *V* and *I* filters were combined. NGC 6745 is a young (~ 200 Myr old) open cluster of about 100 stars situated at about 340 pc in the Galactic Plane. See Photo Release eso1406 for further details.