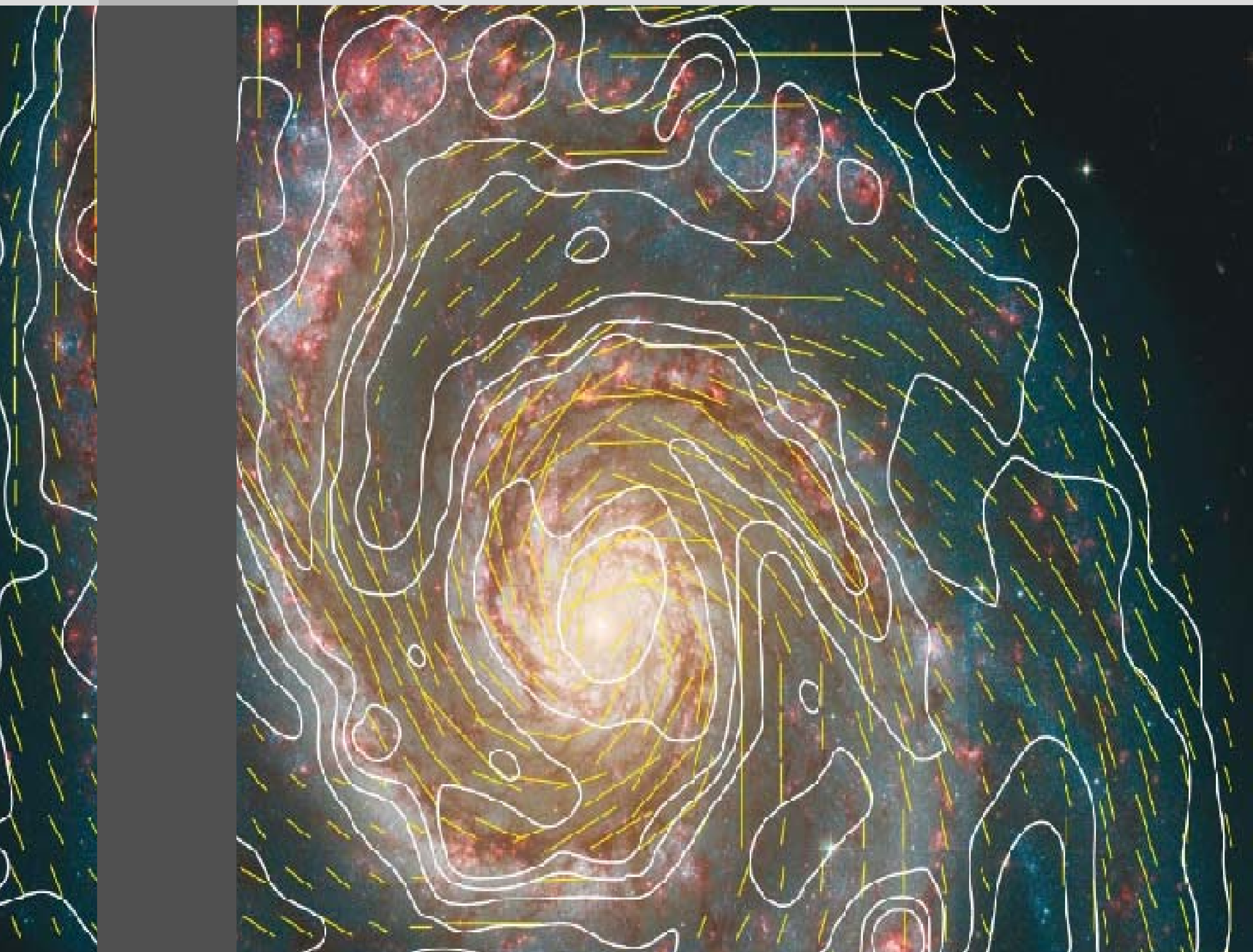
E-ELT Spectropolarimetry: The Science Case

A Community Proposal to ESO (July 2009)



A broad suite of astrophysical projects requiring spectropolarimetry and the E-ELT is presented. Spectropolarimetry not merely sorts photons by their wavelengths but unravels the physics of their history from the emission site all the way to the observer. Elaborating on Solar System bodies and extra-solar planets, the interstellar and intergalactic medium, young, old, and solar-like stars, supernovae, GRBs, galaxies, AGNs, weak cosmic lensing, and even the early universe, a synopsis of the unique benefits of this observing technique is developed. The aim is to stir and guide the discussion about polarimetric capabilities for the E-ELT.

Frontside illustration: Composite image of M51 from HST (optical), VLA, and Effelsberg (radio contours and magnetic-field vectors). Courtesy Rainer Beck, MPIfR, Bonn.

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A. Executive Summary

The E-ELT will, for the foreseeable future, be the most powerful optical light-collecting machine ever built. Since it also absorbs a large amount of financial resources, which other projects may find missing, scientists from all over the E-ELT community are seeking to secure a share for "their" science. Mostly, this will be organized by types of astronomical objects, partly by overarching questions. Polarimetry is different in that it is relevant for a large fraction of all fields that the E-ELT promises to advance, irrespective of age, distance, mass, size, luminosity, temperature, density, etc. But it will favor projects with strong physical ambitions.

Spectropolarimetry accomplishes this advance by widening the spectrum of elementary physical processes, on which models can be based securely. Spectropolarimetry can measure

- ❑ size, shape, orientation, and composition of dust particles (often critical for the determination of extinction values, the uncertainty of which dominates many error analyses),
- ❑ weak reflected-light signatures (*e.g.*, extra-solar planets, hidden nuclei of AGNs, deeply embedded protostars, massive stars with optically thick ejected envelopes),
- ❑ scattering properties of light-reflecting screens (*e.g.*, planetary atmospheres, dust shells, surfaces of rocky bodies, albedos for density measurements),
- ❑ 3-dimensional shapes of point sources independently of distance and separately for physically distinct regions (*e.g.* physics of supernova explosions and aspect-angle dependency of their apparent luminosities),
- ❑ formation of structure at very early epochs (*e.g.*, AGNs, GRBs, dust grains),
- ❑ stellar magnetic fields and their geometry (*e.g.*, star formation, rotational braking, mass loss, convective processes, genealogy of advanced stages of stellar evolution, nature of soft gamma-ray repeaters).

These unique capabilities are enabled by the memory encapsulated in the polarized light imprinted by the physical processes governing the emission of a photon and occurring along its path to the observer. The most singular and universal deliverable is spatial resolution that is limited by flux only, irrespective of angular size (nearness).

Spectropolarimetry often offers results highly complementary to the ones of other observing techniques, can provide clues not otherwise obtainable, is a strictly differential (= accurate) method, can exploit mildly non-photometric nights, increases the cost of a spectrograph by just a few % (but may reduce its overall throughput by no more than 10 % over broad ranges in wavelength), and is photon starved even for some solar applications and thus requires, and optimally exploits, ELTs.

The strength of spectropolarimetry is the anchorage in physics of astronomical observations, making sure that the E-ELT can be credited also for the physical explanation of its discoveries.

Most of the observing projects named in this document can be carried out neither without polarimetry nor without an ELT. There is no substitute for polarimetry, and polarimetry seamlessly complements photometry and spectroscopy. Therefore an ELT will only reach its full promise with commensurate polarimetric capabilities.

B. Background and Purpose of this Document

The power of polarimetry

Polarization and wavelength are the bits of information attached to every photon that reveal the most about its formation and subsequent history. In a purely observational science such as astronomy, this carries even higher weight because polarimetry goes directly to the heart of the problem, *i.e.* the underlying physical process. The elementary processes are anisotropic radiation, asymmetric geometry, and magnetic fields. Among the most wide-spread astrophysical examples are:

- Reflection off not significantly self-luminous screens
  - to analyze the reflectors (*e.g.*, exoplanets, remote mineralogy of bodies with solid surfaces),
  - to study sources not directly visible (*e.g.*, AGNs).
- Scattering (*e.g.* by dust particles in the interstellar medium).
- Symmetry of not otherwise resolved structures (*e.g.*, supernova explosions, AGNs, jets, spots, disks, occulting structures, dust particles in magnetic fields).
- Coherent scattering in spectral lines (*e.g.* in magnetospheres).
- Zeeman and Paschen-Back effects in magnetic fields (*e.g.* on stellar surfaces).
- Cyclotron or synchrotron radiation (*e.g.* from Galactic large-scale magnetic fields).

The spatial resolution arises if the polarization of a photon is not compensated by another photon scattered at a location 90 degrees away in position angle, leads to be a net polarization (of typically 1% for a 10% global distortion). The inversion of polarization data thus yields a *spatial* resolution that is relatively coarse expressed as a fraction of the linear dimensions of the object studied. But it does not depend on the apparent angular diameter, or proximity, of the object so that the *angular* resolution is effectively not limited.

Most targets will be point sources or dominated by small angular-scale structures. Therefore, AO-supported polarimetry benefits from the D^4 law of increased telescope diameter, D. At the same time, the extractability of polarimetric spatial information depends solely on the collected flux. By contrast, the angular resolution of phased multi-aperture or single-dish telescopes only scales with $1/D$ so that a hypothetical extremely large interferometer would need to be truly extreme in order to win over polarimetry.

Therefore, the combination of polarimetry with spectroscopy permits a refinement of the resolution within the plane of the sky and a radial dimension to be added where zones with different physical conditions (temperature, chemical composition, expansion velocity, radius, rotation, etc.) are also polarimetrically distinguishable. This renders spectropolarimetry a high-performance and far-reaching tomographic tool.

In order to explain complex spectroscopic and photometric observations of accretion processes, collimated jets, rotational braking, coronal heating, non-spherical geometries, and many others magnetic fields are frequently invoked. But only polarimetry can detect and measure magnetic fields and so substitute facts for speculation[2]. Magnetism is one of the four fundamental forces in

[2] As an often-heard joke puts it: '*To understand the Universe, we examine galaxies and stars for radiation, small- and large-scale motions, temperatures, chemical composition, and much more. Anything we can't explain after that, we attribute to magnetic fields.*'

nature. Understanding the Universe is impossible without understanding cosmic magnetism, which plays an important role in the formation of celestial bodies and their evolution as well as during the early stages of the Universe (*e.g.* Rees, 2005, in *Cosmic Magnetic Fields*, Springer, p.1; Gaenslera, Beck & Feretti, 2004, *New Astron. Reviews* 48, 1003).

Spectropolarimetry extends substantially the volume of the observational and physical parameter space into additional dimensions often not or poorly sampled by conventional imaging and spectroscopy. Observation-technically this extension does not cause conflicts. On the contrary, all combinations, namely

- Imaging and broad-band photopolarimetry
- Spectropolarimetry
- Spectropolarimetric interferometry

are possible without detriment to the photometry, spectroscopy, or interferometry. In fact, an instrument that satisfies polarimetric requirements will easily fulfill other specifications on the quantitative calibration. The polarization requirements will not generally be in conflict with other performance parameters.

Polarimetry is a natural driver for quality. Since the polarizing processes considered here rarely exceed a few percent in the degree of polarization, then many applications will typically aim for an accuracy of about one tenth of the value, hence 0.1%. This level of accuracy is not obviously in conflict with the state of the art achievable with current astronomical instrumentation. However it must be achieved for the faintest and the brightest sources in order to enable the science goals outlined here to be met. Collecting enough photons for polarimetry at this level will not be problematic for an ELT, but the requirements on dynamic range of the detectors and intrinsic stability of the instruments and detectors remain demanding.

Per wavelength resolution element, polarization detectable at the 0.1% level translates into a few million photons. For many classes of objects, even 8-m telescopes quickly run out of power when confronted with such a task. Therefore, as soon as the scientific objectives under consideration reach beyond the mere detection of an object, there is no stronger justification for increased telescope diameters than from spectropolarimetry. In fact, since modern detectors will reach negligible read noise levels, equipment that can measure polarization to better than 0.1% can also detect very dim sources.

In polarimetry, the E-ELT will not do 8-m class science with shorter exposure times. Many of the science cases discussed below will only be enabled by the E-ELT. This is further compounded by the variability of many types of sources, which in the environment of compact objects tends to be rapid. Non-repetitive eruptive or explosive events are either observed properly or missed, as is obvious not just in the case of GRBs.

For targets with a *V* magnitude fainter than 15 (bright nights) and 21 (dark nights) the sky brightness decreases the limiting sensitivity for any telescope aperture unless AO is used for diffraction limited imaging. Therefore, AO-based polarimetry may be a second-generation application, in particular at optical wavelengths. Any extended object resolved by the E-ELT adaptive optics would also provide unique science opportunities through polarimetry. The thrust of first-generation applications would be on spectropolarimetry of point sources or easily resolved extended sources.

Purpose of this document

A highly impressive body of scientific applications and derived requirements has already been established in support of the E-ELT, and it is still growing with every new discovery made (or questioned) with current facilities. There is no doubt that they make the strongest possible case for such an ambitious project.

On the other hand, the E-ELT aims for the caliber of UNESCO World Heritage objects. Actually, the E-ELT will be more unique than many of the latter. And its mission lies in the future rather than the past. Therefore, it would be regrettable if the E-ELT seriously curtailed its expected long-lasting contribution to the scientific world heritage by not exploiting the full electro-magnetic information.

Several Science White Papers (Clemens et al. [2x], Hines et al., Hoffman et al., Wang et al., all available at http://sites.nationalacademies.org/bpa/BPA_050603) prepared for the 2010 US *Astronomy and Astrophysics Decadal Surve*y praise as exemplary achievements European polarimetric capabilities established on 4- and 8-m class telescopes. The E-ELT offers the opportunity to further expand this European stronghold.

The present document compiles a broad range of high-potential polarimetric applications of the E-ELT. Unavoidably, it is imbalanced and incomplete. But it is sufficient to demonstrate that the scientific return of the core capabilities of the presently planned suite of instruments will be substantially increased when combined with the power of polarimetry. The document does not compete with polarimetric science cases prepared in support of EPICS, METIS, or other E-ELT instrument studies. Rather, it supports any effort to make them and others become feasible.

Other generalized science cases for polarimetry were recently prepared by Wang et al. (2009, *Astro2010: The Astronomy and Astrophysics Decadal Survey*, Science White Papers), in Strassmeier et al. (eds., 2009, IAU Symp. 259, "*Cosmic Magnetic Fields: from Planets to Stars and Galaxies*", Cambridge University Press), by Baade et al. (2006, IAU Symp. 232, "*The Scientific Requirements for Extremely Large Telescopes*", p.248), and for major sub-areas in the contributions to the *US 2010 Decadal Survey of Astronomy and Astrophysics* referenced above. In particular, a group of 29 US-led investigators prepared a White Paper supporting polarimetry with the LSST entitled "An All-Sky Optical Polarization Survey with the LSST"[3]. Solar System spectropolarimetry was reviewed by Boehnhardt et al. (2009, in *Earth, Moon, and Planets*, Springer, online).

[3] Available at http://www.astro.iag.usp.br/~mario/PAPERS/LSST_Polarimetry_rev.pdf,

C. Science Cases

C.1. Extra-solar Planets and Solar System Objects

The quest for exoplanets

Existing equipment has proven to be quite effective in detecting exoplanets indirectly through their interaction (radial velocity, proper motion, eclipses, etc.) with their host stars (*cf.* J. Schneider's regularly updated compilation at http://exoplanet.eu). With the results from future facilities such as *CoRoT, Kepler*, *Gaia,* and SPHERE/VLT, the statistics of extra-solar planets will be on a very firm footing. This kind of data also permits surface properties of the planets to be guessed from the distance to the host star and its luminosity and surface temperature. The light-collecting power and angular resolution of very much larger telescopes become indispensible when measurements of the actual physical properties require analysis of the light reflected by the planets. The task of characterizing exoplanets will become a major field of endeavor, with the identification of potentially habitable planets as a key driver.

Exciting progress is being made already, giving a glimpse of what the E-ELT may achieve. In the brightness variations of a giant eclipsing planet, the *CoRoT* satellite has detected the differences between the illuminated and the dark hemisphere (Snellen et al., 2009, *Nature* 459, 543). The presence of an atmosphere and a value of the albedo were derived. Evidently, spectra would reveal incomparably much more information, only to be further surpassed by low-resolution spectropolarimetry. The latter is not nearly as elusive a goal as it may sound because one of the most promising methods for the direct detection of light from exoplanets is polarimetry. The light reflected off a planet is polarized by up to ~20% in the optical, and, in marginally resolved systems, polarimetry strongly enhances the contrast between the diffuse direct and the reflected stellar light. This strategy, combined with techniques to suppress much of the stellar light, is being pursued by SPHERE/ZIMPOL (Beuzit et al., 2008, SPIE, 7014, 701418) on the VLT and EPICS (Kasper et al., 2008, *SPIE* 7015, 70151S) on the E-ELT and also is central to the E-ELT Design Reference Mission Plan.

An alternative technique for the characterization of the atmospheres of exoplanets is the analysis of absorption spectra when the planet is transiting the disk of its host star. But this drastically reduces the number of systems, to which the method is applicable, makes observations time critical, and fails for planets without an atmosphere. Spectropolarimetry is at hand for all out-of-eclipse situations.

The first detection of polarized reflected light from an extra-solar planet's atmosphere was reported by Berdyugina et al. (2008, *ApJ* 673, 83). The derived orbital parameters are in good agreement with other techniques, and from the scattering properties the radius of the atmosphere was estimated to exceed the one of the opaque body by ~30%. However, confirmation of the observations is pending (*cf.* Wiktorowicz, 2009, *ApJ* 696, 1116). Promises are also good to detect and follow the transits of planets in front of their host stars. Such an occultation breaks any spherical symmetry over the projected stellar disk and thus results in a non-vanishing linear polarization (Carciofi & Magalhaes, 2005, *ApJ* 635, 570).

The following subsections summarize what has been learned from polarimetry in the solar system. In a scaled-down version, they give a preview of what, in principle, spectropolarimetry can do for exoplanets, and the emphasis on historical work is intentional. Since the scope of the E-ELT will not be restricted to Earth-like planets, there is a high chance that all examples will materialize one way or the other. Current estimates do not positively predict the detection of a habitable planet by the E-ELT. But, by supporting spectropolarimetry, the E-ELT should make sure that, if it does succeed in such an epochal discovery, there is no built-in restriction on the observational follow-up.

At the other extreme, E-ELT polarimetry of Solar System bodies not only is not absurd but opens unprecedented science opportunities even after fly-by and landing missions to all solar planets (which are bright but mostly rapidly rotating and also otherwise locally rapidly variable). At a time of disquieting changes of the terrestrial climate, the study of other planetary atmospheres is more important than ever.

Planetary atmospheres

If the light scattering follows the Rayleigh law, the strongest polarization is perpendicular to the scattering plane (defined by the triangle Star-Planet-Earth because it is the plane of symmetry). In the case of Mie scattering, the polarization can be radial with respect to the source and the net polarization tilted with respect to the scattering plane. In the mid-1920s, Bernard Lyot applied polarimetry to infer that Venus's atmospheric structure consists of droplets, like rain on Earth. Spectro-photopolarimetry from the UV to the IR has enabled researchers in the seventies to map Venus's detailed cloud structure (Dollfus & Coffeen, 1970, *A&A* 8, 251).

In the 1980s, spectropolarimetry of Martian dust storms indicated that the scattering particles are solid grains measuring less than one micrometer. This proved consistent with the assumption that they have been lifted from the ground by the strong winds, which occur during the warmer periods on Mars (Ebisawa & Dollfus, 1993, *A&A* 272, 671).

Below the thick atmosphere of Titan or the crust of Europa, liquid surfaces less hostile to life than on other satellites may exist. The degree of polarization from Titan's atmosphere was found to be as high as 50% in blue light, indicating a Mie- rather than Rayleigh-type scattering process with an altitude-dependent particle-size distribution. Sunlight breaks down the methane and forms other chemicals, which create layers of haze or smog in Titan's atmosphere (*cf.* results from the Cassini-Huygens spacecraft).

Jupiter exhibits a latitude-dependent polarization that increases towards the poles, in particular at short wavelengths (*e.g.* Hall & Riley, 1974, in *Planets, stars and nebulae studied with photo-polarimetry*, ed. T. Gehrels, Tucson, Univ. Arizona Press, p.593), and exhibits a north-south asymmetry with orbital (seasonal) variations revealed by long-term polarimetric monitoring (Shalygina et al., 2008, *Solar System Research* 42, 8). At the poles the polarization degree reaches almost 50% whereas the dark bands or the Great Red Spot do not carry a particularly obvious polarimetric signature. A conceivable interpretation includes a hazy top atmospheric layer with increased optical thickness over the poles. HST has imaged extended aurorae on Jupiter's poles and these may actually be the source for the increased polarization. The E-ELT could map and probe these aurorae in great detail (see also Kasper et al., 2008, *SPIE* 7015, 70151S for the extra-solar case).

The polarization of Saturn's rings is extremely complex and has been extensively discussed in terms of multiple scattering, coherent back-scattering, ephemeral radial features shadowing the ring, and others (*e.g.*, Dollfus, 1996, *Icarus* 124, 237; Provan et al., 2009, *JGR* 114, A02225). The realization that part of the ring system is replenished by the volcanic activity of Enceladus has strongly reinvigorated the desire for new observations at high spatial and good temporal resolution (*cf.* the early work by Goguen & Sinton, 1985, *Science* 230, 65 on the volcanic activity of Io). They would join with much improved numerical hydrodynamics, which would also embrace polarimetric observations of the rings around the other gaseous giants.

Phase-dependent variations in the polarization of methane bands at 682nm led Schempp & Smith (1984, *Icarus* 57, 228) to conclude that Uranus has an upper atmosphere with aerosols that scatter according to a Rayleigh law. (Note that, in outer solar-system planets, the swing in illumination phase is very small, whereas for exoplanets the full range is accessible.)

Solid surfaces

The dielectric state of a reflecting and/or scattering surface introduces a certain preference in polarization angle, which is wavelength dependent. The lunar surface shows high spatial frequency polarimetric structures not resolved by seeing-limited data. On larger scales, the Moon's dark maria are more polarized than the bright highland terrains (Coyne & Pellicori, 1970, *AJ* 75, 54). The difference in polarization between Mercury and the Moon (Gehrels, Landau & Coyne, 1987, *Icarus* 71, 386) is only minor, and also the polarization of terrestrial volcano lavas is similar to the one of the lunar surface. A wide range of measurements is available from asteroids (Belskaya et al., 2009, *Icarus* 199, 97). The resulting albedo-polarization relation may be profitably employed for future mineralogy of rocky extra-solar planets and Solar System moons, trans-Neptunian objects (TNOs; for first VLT results see Bagnulo et al., 2006, *A&A* 450, 1239), asteroids, and near-Earth objects (NEOs). The probably unsurpassed look-back time afforded by TNOs will extend Solar System genealogy to a very early phase. Very importantly, polarimetric albedos will permit the determination of the sizes and densities of unresolved objects (Delbo et al., 2007, *Icarus* 188, 266), among which NEOs may be especially critical. For this application, the mid-infrared wavelength range is particular valuable (Johnson et al., 1994, *JGR* 99, E10, 21121).

Magnetism

Complex organic life on Earth may not have developed if the magnetic field of the Sun and Earth did not protect the Earth from cosmic rays (*e.g.*, Shaviv, 2003, *JGR* 108, 1437). Recent studies have found enhancements in chromospheric-activity indicators in planet-hosting stars that vary with the orbital period, suggesting that some extra-solar planets may indeed possess magnetic fields (Shkolnik et al., 2008, *ApJ* 676, 628). But these perturbations may also be of a different nature and require a more direct confirmation. Polarimetry with the E-ELT offers the opportunity to measure magnetic fields of exo-planets and thereby add a decisive criterion to distinguish between exoplanets in a habitable zone that are or are not habitable by terrestrial life.

The Vegetation Red Edge and other terrestrial-life markers

Vegetation has a fivefold higher reflectivity in the NIR than in the optical domain. The steep drop around 700 nm is called the Vegetation Red Edge (VRE). It has been detected in earthshine observations off the face of the Moon (*e.g.* Hamdani *et al.,* 2006, *A&A* 460, 617) and will be a prime target for E-ELT broad-band observations in integrated light. However, the spectral region of the VRE is contaminated by unknown amounts of O_3 absorption (plus O_2 bands). A possible way out is to observe in polarized light and use the known albedo-polarization relation for planetary surfaces. Polarization degrees of up to 20% are expected from planets in short-period orbits. Low spectral resolution (*e.g.*, the $R \approx 50$ polarimetric mode of EPICS or slightly better) but extremely low instrumental polarization are required for its detection.

The development of terrestrial life may have been helped through seeding by comets. Many molecules are biologically relevant in only one of their two chemically equivalent chiral forms. The origin of this peculiarity is not known. For instance, a chiral imbalance may have arisen from irradiation by circularly polarized starlight, in which case the chirality of terrestrial life would possibly be a mere coincidence. A recently analyzed meteorite suggests that chirality was, in fact, a property of very early solar-system material (Pizzarello et al., 2008, *PNAS* 105, 3010). For the more pertinent gaseous matter, circular spectropolarimetry is the analysis method of choice and needs to be applied to cometary tails, the interstellar medium, and even exoplanets. Circular polarization has possibly been detected in the spectrum of the Earthshine and may be interpreted as signature of biomatter (chlorophyll in particular) on the Earth's surface (Sterzik & Bagnulo, http://www.sc.eso.org/~msterzik/BioAstro07/Bioastro07.pdf).

Comets

Resonance scattering excited by the solar radiation is the source for spectral polarization features in the light of molecular bands of comets. Light scattered by small particles, mostly dust, rather shows a continuum. Spectropolarimetric E-ELT observations that allow the individual rotational-vibrational lines in the spectrum of various sections of a comet's core to be resolved will give direct insights into the chemical stratification and evaporation processes of comets (Kolokolova et al 2004, in *Comets II*, eds. M. Festou et al., Univ. Arizona Press, p. 577). Outgasing events in comets (*e.g.* Rosebush et al., 2009, *J. Quantit. Spectrosc. and Radiative Transfer* 110, 1719) and cometary asteroids at large solar distances can only be investigated with an ELT. The simultaneous presence of gas and dust could provide dual diagnostics but the weakness of the polarimetric signal from the gas component has prevented this potential to be exploited with existing equipment. The observing techniques are comparable to the ones needed for the interplanetary (molecular) medium (*e.g.* Levasseur-Regourd, Hadamcik & Renard, 1996, *A&A* 313, 327). Because the Doppler effect shifts the reflected sunlight, good spectral resolution is needed to uniquely identify and interpret the rich line spectrum from the many molecular species (C_2, C_3, CN, OH and others). Particularly challenging targets are the nuclei of comets but permit their surfaces to be compared to those of rocky Solar System bodies in an effort to study the history of the Solar System (Boehnhardt et al., 2008, *A&A* 489, 1337). Comets are also sensitive probes of the interplanetary space as such, especially at high ecliptic latitudes.

For extra-solar comets see Sect. C.3.

Extra-solar planet and solar-system science enabled by spectropolarimetry with the E-ELT

- Direct detection of exoplanets in scattered light.
- Physical characterization of atmospheres of exoplanets (stratification, large-scale asymmetries, etc.) without restriction to transits.
- Remote mineralogy of rocky exoplanets and solar-system moons, TNOs, asteroids, and NEOs, incl. size and density measurements from polarimetric albedos.
- Search for magnetospheres around exoplanets as a possible requirement for habitability.
- Time- and position angle-dependent studies of the rings around Saturn and other giant planets.
- Volcanic activity of solar-system moons.
- Chemical stratification and evaporation processes in comets.
- Origin of chirality in terrestrial biochemistry.
- Verification, using an albedo-polarization relation, of Vegetation Red Edge detections.

C.2. Stellar Formation, Structure, and Evolution

Protostars: the link to the star formation process

Magnetic fields are important ingredients of the star formation process (McKee & Ostriker, 2007, *ARA&A* 45, 565). Models of magnetically driven accretion and outflows successfully reproduce many observational properties of low-mass pre-main sequence stars. Indirect observational evidence for the presence of magnetic fields in these stars manifests itself in strong X-ray, FUV, and UV emission (*e.g.*, Feigelson & Montmerle, 1999, *ARA&A* 37, 363).

The first detections of magnetic fields in protostars of class I and II sources were obtained using NIR spectrographs and reveal kG fields (*e.g.*, Johns-Krull et al., 2009, *ApJ* 700, 1440). A VLT surface map in Stokes I of a young star in the Lupus star-forming region revealed the regions of impacting circumstellar matter (Strassmeier et al., 2005, *A&A* 440, 1105). The accreted matter is presumably funneled along magnetic field lines but lack of spectropolarimetry prevented the full empirical verification of this model. The first magnetic-field maps of T Tauri stars show some systems that have complex fields while some have much simpler dipolar/octupolar fields (Hussain et al., 2009, *in IAU Symp. 259, p.447;* Donati et al., 2008, *MNRAS* 386, 1234). Accretion models based on these maps demonstrate the strong dependence of accretion efficiency on both the size and geometry of the star's magnetic field. Fields have also been detected in half a dozen Herbig Ae/Be stars (*e.g.* Hubrig et al., 2009, *in IAU Symp. 259, p.395*). The magnetic field strength and the X-ray emission of Herbig Ae/Be stars show hints for a decline with age in the range of ~2–14 Myr supporting a dynamo mechanism that decays with age.

Very few systems can be studied even with 8m-class telescopes; high-resolution spectropolarimetry at NIR and MIR wavelengths would enable a large step forward in the understanding of star formation. Complex theories have been developed based on indirect indicators of magnetospheric accretion; high-resolution spectro-polarimetry in all Stokes parameters is essential in testing them.

Magnetic braking and ambipolar diffusion in metal-poor protostars

Magnetic braking of rotating, slowly contracting, self-gravitating protostellar cores via torsional Alfvén waves coupled to the surrounding cloud medium can help to solve the angular-momentum problem in low-mass star formation (*e.g.* Basu & Mouschovias, 1995, *ApJ* 452, 386). The theoretical prediction is that the ambipolar diffusion timescale is shorter for lower-metallicity molecular gas (owing to the lower fractional degree of ionization). Thus the collapse of proto-stellar cores in metal-poor conditions (such as in the LMC/SMC and in the early Galactic halo) would result in higher angular momentum systems. An inside-out dynamical collapse (somewhat retarded compared to free-fall without magnetic forces) would cause the pre-stellar core to turn into a real protostar, including a magnetized rotating disk and bipolar jet. Detecting the magnetized disk would be the most direct verification of this scenario and requires polarimetry at optical and NIR wavelengths with an ELT.

Circumstellar disks and planet formation

The inner structure of protoplanetary disks, *i.e.*, the presumed locus of the formation of planets mostly unresolved with current instruments. Spectropolarimetry can overcome this limit as the result of absorptive linear polarization due to anisotropic radiation (Harrington & Kuhn, 2008, *ApJ* 695, 238). This effect allows inhomogeneities in the inner circumstellar environment to be detected. With the E-ELT it can be fully employed for studying clumpy structure of protoplanetary disks in Ae/Be stars, evaluating the gas/dust ratio in planetesimals and the disk, and shedding light on the dark age of accretion processes and planet formation.

Various types of stars, *e.g.* Vega and β Pictoris, are known to have retained a debris disk. Observations with NACO of β Pictoris are highly suggestive of the presence of a planet (Lagrange et al., 2009, A&A, arXiv: 0811.3583; see also Lecavelier des Etangs & Vidal-Madjar, 2009, A&A, arXiv: 0903.1101). The ability of spectropolarimetry to identify and characterize circumstellar disks (owing to the asymmetry introduced by them) was obviously not needed in this very bright and nearby star. Instead, spectropolarimetry could in this particular case go a fascinating step farther: In optical high-resolution spectra, Lagrange-Henri et al. (1992, *A&A* 264, 637) detected narrow variable and always redshifted absorption lines, which may be due to evaporating comets spiraling in to the central star. Polarimetric observations at higher spectral resolution than hitherto possible will enable significant progress in the knowledge about comets also in the young solar system, when they were much more abundant and important. Unlike pure absorption spectroscopy, the scattering seen in polarization also samples processes outside the line of sight. In addition, it will make it possible to extend such studies to the structure and dynamics of disks around cooler stars. (For comets in the solar system see Sect. C.1).

At the hydrogen-burning limit: magnetic fields in fully convective stars

There are competing theories on the type of dynamo mechanism operating in fully convective stars. To down-select them, it is necessary to measure differential rotation and the magnetic field configuration of stars from late-M types to the limit of stellar hydrogen burning (see Donati *et al.,* 2006, *Science* 311, 633). Only the brightest M-type stars can currently be studied in this manner. Recent results suggest that very low mass stars down to ~0.09 M_{Sun} possess strong kG fields (Reiners, Basri & Christensen, 2009, *ApJ* 697, 373). However these are just based on Stokes I observations; analysis with Stokes Q, U, and V is needed for a more complete understanding. Objects below the hydrogen-burning limit may possess magnetic fields, but these are very hard if not impossible to detect with 8−10m class telescopes.

A straightforward goal for the E-ELT would be to detect and then map magnetic fields on the surfaces of brown dwarfs around the hydrogen burning limit.

Magnetic history of the Sun: analogs in open star clusters of different ages

In late-type stars, magnetically driven winds enable stars to lose angular momentum over the course of their main-sequence lifetimes. It has long been established that the efficiency, with which stars spin down, is mass dependent, with low-mass, fully convective stars taking 10 times longer to spin down than their higher-mass (>0.5 M_{Sun}) counterparts. The efficiency, with which stars spin down, is highly dependent on the geometry of the magnetic fields, i.e., how starspots are distributed (*e.g.*, Strassmeier, 2009, *A&ARev.* 17/3, in press). Doppler imaging (tomographic) techniques applied to time series of Stokes V spectra in order to map magnetic fields across the surfaces of the brightest and most active rapidly rotating stars led to surprising results. A strong field of over 100 G covers almost the entire observable surface in active stars, while independent molecular band studies indicate the presence of large spots covering up to 50% of their surfaces. Recent works have suggested that the geometry of magnetic fields depends on rotation rate and convection zone depth, with low-mass, fully convective stars showing simpler fields (Donati et al., 2008, *MNRAS* 390, 545; Reiners & Basri, 2009, *A&A* 496, 787). However, searches for magnetic fields in Stokes V often have to resort to multi-line cross-correlation techniques in order to lift the signal-to-noise ratio above the significance threshold (polarization signature is ~10^{-4} I_c). Stokes Q and U signals are even expected to be a factor of 10 weaker.

The E-ELT can detect and map magnetic fields even in low-activity stars, i.e. in true solar analogs. Currently, measurements are limited to the handful of brightest and most active stars. To understand the Sun's evolution, it is necessary to study stars at comparable activity levels and convection zone depths. These stars can be found in open clusters of well-defined age but at magnitudes too faint for high-resolution spectropolarimetry with an 8-10m class telescope. Observations with the E-ELT would disclose how magnetic field geometries change with age and mass and how angular-momentum loss and stellar evolution beyond the Vogt-Russell theorem are affected. These results would feed directly back into dynamo and flux-emergence models and help to better understand long-term activity behavior on the Sun.

Multi-wavelength spectropolarimetry in the optical and in the NIR would allow to map the atmospheric magnetic field in three dimensions using different diagnostics, *e.g.*, employing multiple atomic and molecular species formed at different heights, thus building a 3-D picture of magnetic fields in stars other than the Sun. This will set a new milestone in our understanding of stellar magnetism.

Massive stars: formation, evolution, and impact on the interstellar medium

One of the longest standing questions about massive stars concerns their process of formation, with disk accretion and mergers being the strongest contenders. In principle, linear spectropolarimetry can unequivocally diagnose a disk (*e.g.*, Vink et al., 2002, *MNRAS* 337, 356). But current telescopes can only reach stars up to the limit near ~10 M_{sun}, above which radiation pressure very strongly counteracts disk accretion. Even the nearest OB associations such as Cyg OB2 call for ELTs.

Massive stars usually end their evolution with a final supernova explosion, producing neutron stars or black holes. Strong magnetic fields may also be involved in the intrinsic asymmetry of core-collapse supernova explosions (see Sect. C.4). The initial masses of these stars range from ~9-10 M_{Sun} to 100 M_{Sun} or more. Magnetic O stars with masses larger than 30 M_{Sun} and their Wolf-Rayet descendants have been suggested as progenitors of magnetars (Gaensler et al., 2005, *ApJ* 620, 95; see also below). But very little is known yet about the existence, origin, and role of magnetic fields in massive OB and Wolf-Rayet stars. The lack of information is especially disturbing because magnetic fields may have paramount influence on the evolution of high-mass stars. Maeder & Meynet (2005, *A&A* 440, 1041) examined the effect of magnetic fields on chemical mixing and the transport of angular momentum and found that the potential influence on the evolution of massive stars is drastic.

Only eight O stars have currently published magnetic fields (*e.g.*, Donati et al., 2002, *MNRAS* 333, 55; Hubrig et al., 2008, *A&A* 490, 793), mostly at the sensitivity limit of current instrumentation. They rely either on high-resolution spectropolarimetry in combination with multi-line stacking or on low-resolution spectropolarimetry, where the magnetic field is measured predominantly in hydrogen and He lines. Information on the behavior of other elements in the presence of a magnetic field can only be obtained with an ELT. The E-ELT can extend such work also to nearby external galaxies with other metallicities so that the interplay of the generation of magnetic fields and magnetically modulated mass loss with metallicity can be better understood.

The mechanisms by which these fields are preserved and generated are of key interest in studies of the X-ray and UV emission. The hot massive stars are the strongest sources of UV radiation which, through resonance scattering of photons by metal ions, produces a strong outflow of material (which has a profound impact on the chemistry and dynamics of the Galactic interstellar medium). An improved understanding of massive stars through the analysis of their high-energy properties linked to the presence of a magnetic field can lead to a better knowledge of several Galactic and extragalactic phenomena (*e.g.* Güdel & Nazé, 2009, *A&ARev.* 17/3, in press).

Chemically peculiar stars

While the vast majority of convective stars (F- to M-types) establish strong evidence of complex surface magnetic fields that are driven by dynamo activity, just 5-10% of all A and B-type stars show chemical peculiarities caused by the presence of strong magnetic fields (Mathys, 2004, in *IAU Symp. 224*, p.225). These “magnetic” stars possess fields that are significantly stronger and more stable than those found in lower-mass stars. The magnetic flux remains constant over the main-sequence lifetime (Hubrig *et al.,* 2007, *AN* 328, 475). The distribution of magnetic fluxes appears to be similar in both magnetic A and B stars and their descendant white dwarfs, with maxima of $\pi R^2 B \sim 10^{27\text{-}28}$ G cm^2 (*e.g.* Ferrario & Wickramasinghe, 2005, *MNRAS* 356, 615), arguing for a fossil field, the flux of which is conserved during stellar evolution.

With the current instrumentation, only a few very bright chemically peculiar stars can be studied in all four Stokes parameters. These are required to obtain more accurate magnetic field maps than from Stokes I and V alone (Kochukhov *et al.*, 2004, *A&A* 414, 613). More importantly, the extension of magnetic studies of chemically peculiar stars to a different metallicity environment in other galaxies is necessary in order to understand the role of the environment on star formation. A few candidates have recently been identified in the LMC using the photometric Δa tool (Paunzen et al., 2006, *A&A* 459, 871), but it is out of reach of spectropolarimetry with presently available 8-10 m class telescopes.

AGB stars and central stars of planetary nebulae

Many, if not all, post-AGB stellar systems swiftly transfer from a spherical to a powerful aspherical pre-planetary nebula outflow phase before waning into a classical planetary nebula (PN). The pre-PN outflows require a mechanism to channel rotational energy into collimated outflows. Radiation and rotation alone are insufficient but a symbiosis of rotation, differential rotation, and large-scale magnetic fields remains promising (*e.g.* Blackman, 2009, in *IAU Symp. 259*, p.35). One appealing paradigm involves accretion onto the primary post-AGB white-dwarf core from a low-mass companion, whose decaying accretion supplies the luminosity. Determining observational signatures of different magneto-hydrodynamic engines is a work in progress. The observation of circular polarization in water masers suggested the existence of a magnetic field of strength 85 mG at a radius of 500 AU in the water-maser source W43 (Vlemmings et al., 2006, *Nature,* 440, 58). For such late AGB and even post-AGB stars, different molecular emissions probe different distances from the central engine, thus requiring NIR wavelengths and large coverage.

From VLT spectropolarimetric analyses of several central stars of PNe, Jordan et al. (2005, *A&A* 432, 273) detected magnetic field strengths of order kG. These authors also estimate that if the fields were frozen into the engine as it evolves to a white dwarf, the fields would be of order MG rather than kG. But flux freezing need not hold, particularly if the field were produced by a dynamo. In any case, kG field strengths are consistent with the environment scaling from the water maser sources. To probe both the central star as well as its PN in circularly polarized light one needs wavelength coverage from the UV to the NIR. Since the expected fields on the surface of an AGB star only reach a few tens of Gauss, very high precision is needed, preferably in all four Stokes parameters. The spectral resolution, on the other hand, can be rather low, of the order of few thousand.

White dwarfs, magnetic genealogies, and cataclysmic variables

Currently about 125 white dwarfs are known to host magnetic fields (see Jordan, 2009, in *IAU Symp. 259*, p.369), which are the remnants of the magnetic fields that the stars hosted over the course of their evolution. Assuming magnetic flux conservation they can reveal the basic properties of even relatively weak magnetic fields on their progenitors. Approximately 10% of all isolated white dwarfs possess fields >1 MG. Given their frequency and spatial distribution, their progenitors are likely to be the magnetic chemically peculiar Ap and Bp stars (Mathys, 2001, in *Magnetic fields across the H-R diagram*, *ASPC* 248, 267).

In other white dwarfs, the field strengths only reach 1-20 kG (Aznar Cuadrado *et al.*, 2004, *A&A* 423, 1081). These stars would have possessed mean surface fields down to 1G during their main sequence lifetimes, permitting much more to be learned about magnetic field properties from low to intermediate mass stars. The relatively high numbers of detections suggest that magnetic fields are common and that they may dissipate strongly by the time they reach white dwarf stages.

The increased sensitivity of the E-ELT could change the whole picture. For instance, the weakness of the magnetic fields may only be apparent at the integral level because the actual field distributions are highly tangled. For the same reason, the very low-field tail, which might include the majority of white dwarfs, may have been missed all together. This can only be revealed by higher spectral resolution, full sets of Stokes parameters, and greater sensitivity. All of these would be given by an E-ELT polarimeter.

In cataclysmic variables (CVs), white dwarfs accrete matter from a late-type companion star. The observed incidence of magnetism in CVs is about 25% (Wickramasinghe & Ferrario 2000, *PASP* 112, 873) and possibly larger than that found in single white dwarfs. The B-field strength distribution of white dwarfs in CVs is much different than that in single white dwarfs with the former peaking at about 38 MG (with extremes in the 100-MG range) while in the latter the most frequent field strength is about 16 MG. However, in CVs one still misses measurements of low-field white dwarfs. This bias could only be rectified with an ELT.

Isolated neutron stars

The remnant of a core-collapse supernova can be a neutron star or, for some scenarios, a magnetar (see also Sect. C.4). The possible origins of the magnetic fields of neutron stars include inheritance from the main sequence progenitor and dynamo action at some evolutionary stage of the progenitor. However, inheritance is not sufficient to explain the GG fields of magnetars. Energetic considerations point to differential rotation in the final stages of the core collapse process as the most likely source of field generation (*e.g.* Spruit, 2009, in *IAU Symp. 259*, p.61), at least for magnetars. Observations of hot-spot thermal X-ray emission from radio pulsars imply that surface magnetic fields at the polar cap(s) are much stronger than the conventional dipolar component estimated from pulsar spin-down. If so, this suggests that the surface field is dominated by crust-anchored local fields. A particularly puzzling problem is the large range of field strengths observed in neutron stars. It implies that a single, deterministic process is insufficient to explain the origin of the magnetic field in these targets. There do not seem to be any obvious examples of such a mechanism in astrophysics. Consequently, direct magnetic-field observations of neutron stars and their progenitors are needed.

Some of the so-called *isolated neutron stars* have a surprisingly large X-ray flux. Since the optical emission of pulsars is generally low (*e.g.* RBS1774 has a Johnson *B* magnitude of 27^m; Schwope et al., 2009, *A&A* 499, 267), their spectra can only be studied with an ELT. A detection of the modulation of its optical flux could possibly provide a first hint at the origin of the GG fields. But for conclusive results polarimetry is required. Note that radio emission maps non-thermal processes and does not originate from the stellar surface but rather from somewhere in the magnetosphere. The E-ELT can provide the first (integral-light) optical spectrum of such a neutron star. The spectrum would require large wavelength coverage but at low spectral resolution if the quadratic Zeeman shifts are to be detected. However, the expected extremely strong Stark effect would possibly broaden the hydrogen lines to the limit of direct detectability. Currently it is not known whether neutron stars have hydrogen lines at all but absorption lines were detected in thermal X-ray spectra. A novel way out would be to employ circular polarization in the blue optical spectrum and search for its rotational modulation.

Soft Gamma-Ray Repeaters (SGRs)

There has recently been growing evidence that SGRs are the population of strongly magnetized neutron stars, so called magnetars[4] (Thompson & Duncan, 1995, *MNRAS* 275, 255). Activities in these objects are believed to be powered by the dissipation of ultra-strong magnetic fields. The giant flare from SGR1806-20 is the most recent and energetic event. It is characterized by an ultra-luminous spike with an energy of 10^{46} erg, which decays rapidly into a soft pulsating tail. Pre-flare activity is additionally detected before the main burst. A rather striking analogy to solar flares is found because coronal mass ejections (CME) on the Sun appear morphologically comparable to those of magnetar flares (Lyutikov, 2006, *MNRAS* 367, 1594). This analogy could be systematically explored with a representative sample of magnetar CMEs. Detecting them even in polarized afterglow light at optical wavelengths would be essential for deducing the flare mechanism.

Stellar astrophysics enabled by spectropolarimetry with the E-ELT

- ❑ Magnetic-field maps on the surfaces of protostars and in disks of T Tauri and Herbig Ae/Be stars.
- ❑ Constraints from molecular-line polarization on magnetic rotational braking as a function of metallicity.
- ❑ History of the solar dynamo from observations of solar analogs in open clusters of different ages.
- ❑ Incidence and importance of magnetic fields in brown dwarfs.
- ❑ Detailed stellar magnetic field topologies beyond the conventional simplifying low-order structures.
- ❑ The shapes and shaping of (pre-)PNe and the evolution of the magnetic fields until the WD phase.
- ❑ Magnetic genealogy of late phases of stellar evolution with important inferences for earlier phases.
- ❑ Detection, in circular polarization, of probably not otherwise visible optical spectral features in isolated neutron stars.
- ❑ Determination of the nature of Soft Gamma-Ray Repeaters from circular polarimetry of optical afterglows.

[4] Currently, 13 magnetars are confirmed (see http://www.physics.mcgill.ca/~pulsar/magnetar/main.html).

C.3. The Interstellar Medium in the Milky Way and other Galaxies

Interstellar dust

Starlight becomes polarized when it is absorbed or scattered by non-spherical interstellar dust grains preferentially aligned by magnetic fields. The distribution of the interstellar polarization is not regular but is highest in the Galactic plane, and the polarization vectors are sometimes strongly correlated (see the review by Jones, 1996, in *Polarimetry of the Interstellar Medium*, *SP* 97, p.381). A significant radiative component of the grain alignment process has been suspected for some time (*cf.* Draine & Weingartner, 1997, *ApJ* 480, 633; Hoang & Lazarian, 2009, *ApJ* 697, 1316) but is still awaiting final observational confirmation from high-quality data. In absorption lines, the position angle of polarization is parallel to the magnetic field lines, while in emission it is perpendicular. Therefore, at MIR wavelengths, coalescing cold (< 100 K) and warm (>200 K) media can be studied simultaneously but separately.

Mid-IR polarimetry is far superior to simple photometric reddening data in characterizing physical dust properties, e.g., mineralogy of bulk amorphous silicates and the distinction of specific dust morphologies such as mantled, separate, or mixed populations. The polarization vector permits the large-scale structure of the interstellar magnetic field lines to be inferred when dust grains align with them, even in the Galactic polar regions (Berdyugin & Teerikorpi, 2002, *A&A* 384, 1050). It may even be possible to estimate the influence of Galactic magnetic fields on star formation from the degree of alignment of the axes of bipolar Herbig-Haro objects (or the planes of protostellar disks) with Galactic magnetic fields (Ménard & Duchêne, 2004, *ApSS* 292, 419).

A good understanding of the variety of dust properties in different environments clearly is a pre-requisite for the proper separation of the foreground polarization from the intrinsic polarization of any object studied. But the importance goes far beyond polarimetry: The diversity of dust properties is so large that for most studies involving absolute luminosities the knowledge of the extinction law will eventually become the limiting factor. Therefore, spectropolarimetry will be an essential co-calibrator even for basic E-ELT applications not in themselves requiring polarimetry.

The Galactic foreground polarization due to dust and synchrotron emission heavily contaminates measurements of the cosmic microwave background (CMB; *e.g.*, Page et al., 2007, *ApJS* 170, 335), and it is of critical importance to quantify it at all wavelengths (Lazarian, et al., 2009, *Astro2010 Decadal Survey White Paper*, BPA_050603).

Spectropolarimetric observations of supernovae and especially GRBs permit the study of interstellar dust out to fairly early phases of the Universe and the identification of the dust-forming processes. Any variation with wavelength in the continuum polarization is ascribed to dust. Observations at late stages permit a further distinction since the dust component should not be variable (unless closely associated with the GRB). Differences between the polarizing and dust properties of galaxies that do or do not host GRBs are also important for the question whether GRB-hosting environments/galaxies have special properties.

Interstellar magnetic fields

Magnetic fields are one of the key ingredients of the interstellar medium (see the review by Han, 2009, in *IAU Symp.* 259, p.455). Large-scale magnetic fields contribute to the hydrostatic balance and stability of the interstellar medium, and even disk dynamics. Magnetic fields in molecular clouds, which are closely related to the Galactic fields, play a strong role in the star formation process. More importantly, the magnetic fields of our Galaxy are the main agent for the transport of charged particles (cosmic rays). It is impossible to understand the origin and propagation of cosmic rays without adequate knowledge of Galactic magnetic fields.

When electromagnetic radiation propagates through a medium with embedded magnetic field, its polarization angle is rotated by the Faraday effect. The polarization vectors show the average field orientation (weighted by the unknown local dust content). Because the angle of rotation increases with the square of the wavelength, magnetic field measurements in galaxies are the domain of radio observations. The Square Kilometric Array will greatly extend the distance limits.

Optical and NIR observations can separate dust and magnetic effects and may also be applicable to high-resolution data of the Lα forest in distant quasars. But their potential scope was recently strongly extended by the so-called Atomic Magnetic Realignment (AMR) effect (Yan & Lazarian, 2008, *ApJ* 677, 1401 and references therein). In its basic form, it has higher sensitivity to weak magnetic fields than the Zeeman effect. Its application to emission lines permits the exploration of relatively high-temperature regions. But it mandates extremely large telescope apertures.

Beyond 2-3 kpc from the Sun, the magnetic field of our Galaxy is not well explored (see Feinstein et al., 2008, *MNRAS* 391, 447). Magnetic fields in the disk-halo interface regions are complex and only few observations are available. The E-ELT can contribute to many of these sub-questions and generate synergy effects with upcoming radio telescopes, which will dominate in the area of extended sources. Note that optical/NIR measurements can provide the *origin* of the polarization direction while, in the radio domain, the Faraday effect induces a *rotation* of the polarization direction. Thus, covering both the radio and the optical/NIR range for such measurements is of high value. Important in this case is large wavelength coverage from the visual to the NIR.

Tinbergen (1982, *A&A* 102, 53) has shown that there is almost no interstellar dust in the vicinity of the Sun. The radius of the cavity is larger than 50 pc in the direction of the Galactic center, and much larger perpendicular to the Galactic plane. The presence of such a local bubble may contain clues for the study of the evolution of our Galactic environment due to past supernovae. The E-ELT can extend the search for such bubbles to more remote parts of the visible Galaxy and thereby map the cavities in the interstellar medium of the Milky Way and further contribute to the explanation of the significant polarization of the “North Polar Spur” (believed to be the remnant of past supernova explosions).

The Galactic Center

The non-thermal radio filaments discovered within one degree from the Galactic Center (*e.g.* LaRosa et al., 2004, *ApJ* 607, 302) indicate poloidal magnetic fields within a few hundred parsecs of the center of the Galaxy. These filaments are highly polarized and almost perpendicular to the Galactic plane although in some newly found examples this orthogonality is less pronounced. The magnetic field is aligned with the filaments, which are probably illuminated flux tubes, with a field strength of about 1 mG. The newly discovered “double helix” nebula (Morris et al., 2006, *Nature* 440, 308), with an estimated field strength of order 100 μG, reinforces the notion of the presence of strong poloidal magnetic fields in tube format emerging from the rotating circum-nuclear gas disk near the Galactic Center. Zeeman-splitting measurements of HI absorption against Sgr A or of the OH maser give a line-of-sight field strength of even a few mG in the clouds. Outside the central region of a few hundred pc to a few kpc, the structure in the stellar and gas distributions and the magnetic structure are all mysterious. In addition to probing the large-scale magnetic fields that should be closely related to the material structure but have not been revealed yet, the E-ELT could also observe the embedded O stars. Since these stars are very young and may not sustain strong internal dynamos, they may still possess an observable memory of the magnetic properties of the matter they formed from. For the Galactic Center, circular spectropolarimetry at very high precision in the NIR up to 2.5μm is required.

Galactic astrophysics enabled by spectropolarimetry with the E-ELT

- ❑ Quantitative extinction data for all studies requiring absolute luminosities, especially for objects without intrinsic color-magnitude calibrations.
- ❑ Study of the formation of dust out to the young Universe.
- ❑ Distant luminous stars as beacons to polarimetrically trace anomalies in the Galactic magnetic field, incl. possible alternative explanation to SNe of dust-free Galactic bubbles.
- ❑ Polarization of extreme Pop. II stars as a tracer of cosmic-ray electrons entering the Galaxy.
- ❑ Helicity of the magnetic field in the vicinity of the Galactic Center at NIR wavelengths.

C.4. Extragalactic Astrophysics and Cosmology

Type Ia supernovae

A topic where linear spectropolarimetry has had a large impact over the last decade is in the study of supernovae (Wang & Wheeler, 2008, *ARA&A* 46, 433, and the references therein). Virtually every supernova that has been properly observed has displayed significant polarization, and hence some significant degree of asymmetry. This has provided new challenges to theory and has shaped the conceptual development of the field. Data has been obtained to crudely sample most of the known types of supernovae. But dense series of data (five observations that is, typically) continue to show a high degree of individuality, and there is a bias to the respective brightest members of each type.

Type Ia supernovae are virtually certain to correspond to C/O white dwarfs that have nearly reached the Chandrasekhar instability limit, given the constraints of UVOIR photometric and spectral evolution. Type Ia supernovae also show significant linear polarization. The polarization decreases with time, vanishing about a week after maximum light, indicating that it is a feature of the outer layers leading to clumpiness of the ejecta. The polarization in Type Ia SNe is especially strong in certain lines, Si II, Ca II and Fe II. The continuum and line polarization are almost surely clues to the thermonuclear combustion processes that explode the star.

A particularly stunning reminder of polarimetric diagnostics unparalleled by more limited conventional observing techniques proved to be the observations by Wang et al. (2006, *ApJ* 653, 490) of SN 2004dt. Ca II 3968, Si II 3859/6355, Mg II 4481, and O I 7774 all had about the same velocity profile. Therefore, on a purely spectroscopic basis, one would have concluded that all these species have about the same radial distribution in the ejecta. Only polarimetry revealed this as a mistake because, contrary to the other species named, O I 7774 was virtually unpolarized. This is an important finding since of the four elements only oxygen is expected to have been present in major quantities before the explosion. Significant constraints on explosion models, *e.g.*, deflagration, detonation, or transitions (Camezo et al., 2004, *Phys. Review Letters* 92, 211102), arise, which require ELT follow-up, especially with a view towards different metallicities and likely ages inferred from the timing of star bursts.

The degree of continuum polarization in Type Ia, less than 0.5% in the continuum, implies flattening of at most 5%. This would contribute less than 0.05 mag to the scatter of the absolute-luminosity calibration. This is probably not in itself particularly relevant to the usage of SNe Ia as standard candles, and the cores of SNe Ia are symmetric anyway, but there are surely effects of asymmetry that are relevant as the field struggles to more tightly understand and control systematic effects. Spectropolarimetry could also be a tool by which one checks for any systematic luminosity difference between local and high-z SNe Ia.

A hint that the spread in the intrinsic luminosities of Type Ia SN explosions is accompanied by a spread in the large-scale spatial structure of the ejecta was found by Wang, Baade & Patat (2007, *Science* 315, 212). In a sample of bright SNe Ia, the degree of polarization measured across Si II 6355 five days before *B* maximum light is correlated with the photometric decline rate, Δm_{15}, which is one of the most widely preferred intrinsic-luminosity indicators. Only an ELT can solidify the low S/N basis of such studies and extend them to additional spectral features and diagnostics (especially in the IR).

Core-collapse supernovae

For a variety of core-collapse supernovae – Types IIP, IIn, IIb, Ib, Ic, and the broad-lined Type Ic associated with long-soft gamma-ray bursts – the degree of the linear polarization increases with time and decreasing outer hydrogen envelope mass. This shows that the inner machine of the explosion is the cause of the asymmetry. This realization has provided a new impetus to understand the asymmetry, whether in terms of neutrino transport, standing shock instabilities, magnetic fields, or rotation. The continuum tends to show a mixed polarization angle indicating a preferred orientation, but there is growing substantial evidence for additional non-axial symmetry of the distribution of elemental and ionic species that begs to be more deeply understood because it may hold the key to discriminate between decisive details of theoretical explosion models. The study, by spectropolarimetry, of magnetic fields and rotational distortion in progenitor stars will complement this work. Type IIn and a growing variety of other supernova types show signatures of strong interaction with circumstellar material, whose geometrical and optical characteristics can be probed by spectropolarimetry (*e.g.* Hoffman et al., 2008, *ApJ* 688, 1186; Tanaka et al. 2009, *ApJ* 699, 1119) and can thus provide a link with the asymmetric, clumpy stellar winds of their massive progenitor stars. There is a growing effort to use Type IIP supernovae as cosmological distance indicators. Their asymmetries in shape must be understood in this context since their apparent brightness may be aspect-angle dependent.

Spectropolarimetry of SNe has only been enabled by 8-m class telescopes. Nevertheless, with the exception of rare nearby events, every single SN hits their limits: Late phases of core-collapse SNe are among the most central ones, because they yield the deepest insights into the explosion mechanism and physics, but cannot be reached. The typical spectral resolution is only a few 100 km/s and often drastically lowered by further rebinning, leaving unmined the information contained in multiple velocity components, let alone the changes of the polarization angle across the broad profiles.

Collapsars and optical afterglows of-Gamma Ray Bursters

Some massive Wolf-Rayet stars may collapse to a black hole without leading to a supernova explosion because they are rotating so rapidly that neutrino losses can prevent the formation of a strong outward shock (MacFayen & Woosley, 1999, *ApJ* 524, 262). This is also a widely discussed scenario for long Gamma-ray Bursts (GRBs). At Galactic metallicity, this model should not work because the winds of massive stars carry away very much angular momentum. Claims that GRBs may preferentially occur in low-metallicity environments (*e.g.*, Vreeswijk et al., 2004, *A&A* 419, 927) could resolve this dilemma but are also facing some critique. The necessary observational verification requires linear spectropolarimetry because rotationally induced wind asymmetries need to be used as a substitute for stellar line widths, which cannot be observed through the dense winds. This has to be done in the SMC, where 8-m telescopes can at best reach the very brightest WR stars (Vink, 2007, *A&A* 469, 707).

Several central scientific goals call for multi-wavelength polarimetry of optical/NIR GRB afterglows: (1) Verification of the intrinsic nature of the radiation itself (broad-band, continuum), (2) analysis of the magnetic field configuration in the relativistic outflow (broad-band), (3) study of the physical nature of GRB light curve breaks to test the jet hypothesis (broad-band), and (4) investigation of the explosion asymmetry of the GRB progenitor (in the case of long bursts via broad-band observations and spectropolarimetry of any detectable SN component).

Progress in this field is slow due to the notorious mismatch between faint, rapidly evolving events and telescope size. Twelve years after the first observed optical afterglow, only one detailed long-term polarimetric light curve of a GRB afterglow could be obtained (GRB 030329 using 50 hrs at the VLT; Greiner et al., 2003, *Nature* 426, 157), while in little more than a handful of other cases (*e.g.*, Hjorth et al. 1999, *Science* 283, 2073) only some scattered data points or upper limits could be obtained. In GRB060418 an upper limit of 8% was measured (Mundell et al., 2006, *Science* 315, 1822), and for GRB090102 a detection was reported (Steele et al., 2009, *Nature*, submitted).

These results represent the current state of the art, both observationally and theoretically, by providing constraints on the magnetic field configurations in a GRB with (090102) and without (060418) bright reverse shock optical emission (an intrinsic property of magnetized fireballs). Bright reverse shock emission, despite theoretical predictions to the contrary, has been shown to be rare in the Swift era and bright bursts fade rapidly; therefore there is strong observational and theoretical motivation to *a)* increase the number of detectable bursts and *b)* extend the temporal range for the monitoring of the spectral evolution of the early-time polarization and its position angle as the afterglow fades. The latter is also essential for the critical proper (vectorial) subtraction of the foreground polarization. This can only be achieved by an increase in the limiting magnitude of the measurement from the current V~17 mag. Due to the rapid fading of the GRB, the measurement is photon count limited. Using an ELT, a simple scaling of the current sensitivity predicts a limit of V~20 mag with a time resolution of ~10 minutes, thereby ensuring a complete sample could be built of all types of optical afterglow, rather than just the very brightest (and hence intrinsically anomalous) events as now.

Active Galactic Nuclei (AGNs) - spectropolarimetry as a periscopic tool

A scattering screen may serve as kind of a mirror of a source, from which all photons emitted in the direction of the nominal line of sight to the observer are blocked by some obscuring structure. Spectropolarimetry separates the scattered flux from the general background. This fact has been instrumental for the establishment of a unified model for AGNs, in which the main difference between galaxies of types Seyfert 1 and 2 lies in a torus which, depending on aspect angle, does (Seyfert 2) or does not (Seyfert 1) prevent the direct observation of the broad-line region surrounding the nucleus (*e.g.*, Antonucci & Miller, 1985, *ApJ* 297, 621; Wolf & Henning, 1999, *A&A* 341, 675; Vernet et al., 2001, *A&A* 366, 7). Often, the broad lines are seen in polarized light only (e.g., Tran et al., 1995, *ApJ* 440, 565). In this picture, which can attain a stunning level of detail (Kishimoto, 1999, *ApJ* 518, 676), the classification into AGNs with and without broad emission lines is only apparent. The scattering medium is mostly dust. The wavelength dependence of the polarization is often Galaxy-like (Solorzano et al., 2004, *MNRAS* 351, 997), with possible differences at higher redshift.

Further exciting inferences become possible regarding the orientation of the torus with respect to a radio jet (Hoffman et al., 2005, *MNRAS* 363, 1241) and the effect of magnetic fields on the alignment of dust grains with respect to the torus and jet (*e.g.*, Oliva et al., 1998, *A&A* 329, L21). Also the properties of the dust itself are of high interest and revealed by polarimetry. The isolation of single events in the vicinity of the super-massive black hole (SMBH) is an important additional prospect. Such observations permit the evolution of the host galaxy to be placed in the fundamental triangle defined by SMBH accretion, jet, and star formation. The proof of principle has been achieved with existing equipment. But its application to objects closer to the redshift of the high-luminosity AGN era requires an ELT.

The exploitation of this periscopic power of spectropolarimetry is not restricted to obscured nuclei of galaxies. It can be equally well applied to still deeply embedded young stellar objects surrounded by reflection nebulae and to near-terminal stellar evolutionary phases such as luminous blue variables like η Car, which are surrounded by massive amounts of ejected matter.

Quasars, blazars, and high-redshift galaxies

The continuum polarization of quasars is a highly effective means to study the geometry, in particular of the powerful outflows, which may be contributing to the nuclear feedback on host-galaxy evolution. Resolution R>5000 is needed to examine the onset and terminal velocities of these quasar outflows and determine the mass entrained in them. Such work is beyond the capabilities of current 8-m telescopes.

The strong Lyα emission seen in many high-redshift galaxies and quasars is often scattered by surrounding neutral hydrogen atoms. Only recently, Dijkstra & Loeb (2008, *MNRAS* 386, 492) have shown that the scattered Lyα radiation obtains a high level of polarization for a wide range of likely environments of high-redshift galaxies. For example, the backscattered Lyα flux observed from galaxies surrounded by a superwind-driven outflow may reach a fractional polarization as high as ~40%. Spectral polarimetry can differentiate between Lyα scattering off infalling gas and outflowing gas: for an outflow, the polarization should increase towards longer wavelengths while for infall the opposite is true. The verification of the polarization of the radiation of high-redshift objects is a premier task for spectropolarimetry with ELTs.

Tori about galactic nuclei usually consist of both gas and dust. Differences between the expansion velocities of the two components provide clues on the acceleration mechanism. Spectropolarimetry can distinguish between photons reaching the observer directly from the emitting gas and photons having been scattered by dust. Since the scattered photons show an additional redshift due to the motion of the dust, the bulk velocities of the two constituents can be disentangled. This technique has been demonstrated for the planetary nebula NGC 7027 (Walsh & Clegg, 1994, *MNRAS* 268, L41) but is equally applicable to AGNs, protostellar disks, and AGB stars.

Cosmic gravitational lensing

Weak gravitational lensing preserves the polarization. Studies of the polarization can, therefore, address two fundamental points: *a)* If the summed-up total polarization of all galaxies in the field under investigation is non-vanishing, the often-made assumption that the true orientation of the lensed galaxies is random may in such cases not be applicable. *b)* A mismatch between the morphology derived from flux data of weakly lensed galaxies and the morphology found in polarization data of the same galaxies provides valuable information about the involved masses (Burns et al., 2004, *ApJ* 613, 672).

Extra-galactic astrophysics enabled by spectropolarimetry with the E-ELT

- ❑ Search for systematic luminosity differences between local and high-z SNe of Type Ia, incl. aspect-angle dependencies due to asymmetries.
- ❑ Measurements at late stages of the intrinsic asymmetry of core-collapse SN explosions; 3-D maps of atomic species in SN ejecta for in-depth comparisons with theoretical models.
- ❑ Physical verification of the jet paradigm of GRBs and the nature of optical afterglows.
- ❑ Time-resolved maps of accretion and jet formation processes close to the central SMBH of representative AGNs and their relation to magnetic fields.
- ❑ Determination of the direction of the net mass in/outflow to/from Lyα-emitting sources at high redshifts.
- ❑ Validation of the assumption of randomly distributed intrinsic position angles of galaxies in weakly lensed fields.

D. Summary, Comparison with other Facilities, and Conclusions

The special and unique sensitivity of polarization to the interaction between light and matter gives polarimetry diagnostic qualities not available with other observing techniques. During the course of the interaction with matter, photons change their polarization properties, either at the level of individual photons or of the net grand-total polarization. In a way, photons retain a memory of these interactions, encapsulating spatial and physical information that cannot otherwise be extracted from unresolved and/or fully obscured sources. The most commonly involved elementary processes are scattering by electrons (or dust) and resonant scattering in ionic transitions; but spatially selective extinction also comes into play. Furthermore, only spectropolarimetry can elevate magnetic fields from a convenient myth to hard-core science.

Under otherwise identical circumstances, spectropolarimetry requires substantially more observing time than other observing techniques. But a single spectropolarimetric observation can often answer many questions that even a very large number of non-polarimetric observations cannot address. For instance, the best of all conventional spectra of a point source cannot tell whether ions exhibiting the same profiles do or do not have also the same angular distribution. And only E-ELT polarimetry is likely to detect and analyze light reflected off exoplanets in 1-AU orbits.

The vast diversity of asymmetric photospheres and scattering screens exceeds the scope of this document. If a trade-off between spectral resolution and wavelength coverage needs to be made, many projects would weight the latter more strongly. Even a condensed, selective enumeration of examples not mentioned above is still impressive. It comprises double or multiple stars (ranging from twins to planetary systems), accretion disks, the structure of mass outflows in massive or evolved stars, eruptive variables, non-radial pulsators, and rotationally distorted stars. The corresponding facts to be learned through spectropolarimetry include the orbital inclination angle i (thus permitting accurate mass determinations, the errors of which increase with the third power of $\sin i$), formation and dissipation processes of circumstellar disks, the physics of mass loss with and without localized substructures (*e.g.*, jets, spots, clumps), pulsation modes and internal stellar structure, and the fractional critical rotation of stars.

The common theme of the very large majority of the E-ELT polarimetry science cases described in Sect. C is very broad wavelength coverage. Even with an ELT, sometimes only the co-addition of spectral lines with similar polarization properties will reach satisfactory levels of significance. Much more important is the inclusion in any single observation of spectral lines forming under different physical conditions (*e.g.*, temperature, density, magnetic field strengths, chemical composition, turbulence, bulk velocity, etc.) because it is the quantitative analysis of physical conditions that lead to the polarization of radiation, where the superiority of spectropolarimetry is largest. Because of the need to study many different physical conditions, no wavelength is clearly preferred. High extinction and the quadratic dependence on wavelength of some magnetic processes favor the (moderately) thermal infrared; but this is not representative.

The distribution of preferred spectral resolving powers is fairly flat from extremely low to extremely high. The polarimetric accuracy should be 0.1-0.5% per spectral resolution element and observation in the degree of the polarization and 1-5 degrees in the polarization angle. Many of the science cases only involve unresolved or marginally resolved sources. Even extended sources may put weaker requirements on the field of view than the possible need (implementation dependent) to use other sources for simultaneous calibration. A significant part of the scientific objectives cannot, or only incompletely, be reached without circular polarimetry. Because of the differential nature of polarimetry, the atmospheric conditions in most cases do not need to be fully photometric (implementation dependent).

Both *ISO* and *HST* implemented polarimetric facilities. In particular *HST* has seen impressive results with many programs benefiting from polarimetry in the optical and near-infrared range. Amongst the recent and near-future infrared space missions (*Spitzer*, *Herschel*, *JWST*), there is no polarimetric option. However, in space, there is an obvious imperative to keep mechanical systems as simple and trouble-free as possible, and in wavelength regions with useful atmospheric transmission, polarimetry can be achieved more effectively from the ground because space-borne facilities cannot (and should not) compete with ground-based ones in terms of light-collecting power. At the same time, AO-empowered ELTs will reach comparable angular resolution as space telescopes. These two facts combined argue very strongly to push the frontiers of astrophysics also by means of E-ELT polarimetry.

The 2007 proposal for the construction for the US Thirty Meter Telescope ignores polarimetry, except in the context of the search for extra-solar planets. Similarly, the Science Case from 2006 for the Giant Magellan Telescope only mentions supernovae explicitly. However, large-area polarization surveys are foreseen with the LSST (Clemens et al., 2009, *BAAS* 41, 459), or are even ongoing at IRSF[5] (Ryo et al., 2006, *SPIE* 6269, 159), and will provide a wealth of polarized targets for the E-ELT.

In conclusion, spectropolarimetry with the E-ELT will

- ❑ serve the entire scientific E-ELT community,
- ❑ add decisive elementary physical information to the endeavor of understanding the Universe from the depths of the solar system to the distant limits of the E-ELT,
- ❑ enable science not possible without an ELT,
- ❑ enable science not possible without polarimetry,
- ❑ not be rivaled by any currently planned astronomical observing facility.

Clearly, these potentials can be realized best if polarimetry is not only enabled at the level of some instrument modes. The very homogeneous requirements on large wavelength coverage as well as the broad, fairly flat needs in terms of spectral resolution suggest that a general-purpose polarimetric facility of the E-ELT may be the most effective. But with some judiciously applied restrictions, the E-ELT will not fall short of the goals developed in this document. A feasibility study of the EPICS exoplanet science case from the telescope point of view could be the most immediate (and urgent) step. In order to strongly encourage a much wider starting scope, the present document is offered.

[5] Japanese Infrared Survey Facility, a 1.4m telescope at SAAO, South Africa. See http://www.z.phys.nagoya-u.ac.jp/~irsf/index_e.html