Spectropolarimetry:

Some of the Most Exciting Science Opportunities Afforded by the E-ELT

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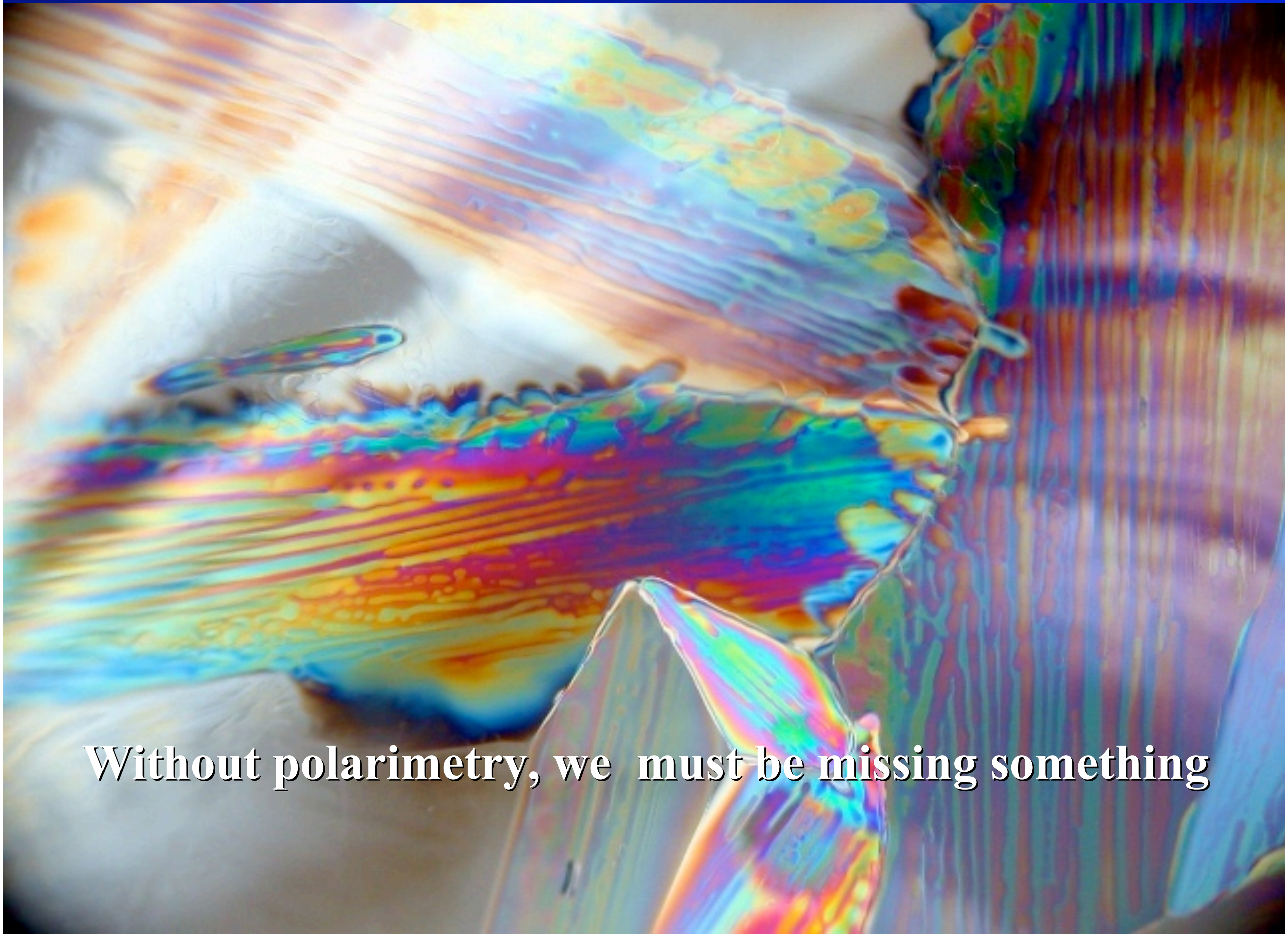
There are 8 electromagnetic observables:

1) coordinate X
2) coordinate Y
3) time
4) frequency
5) flux

Most instruments stop here

… and even some visions, too

6) degree of linear polarization
7) angle of linear polarization
8) degree of circular polarization


Without polarimetry, we must be missing something

In fact: Light can be polarized owing to (at least):

- **cyclotron or synchrotron radiation**
- **scattering by dust particles**
- **absorption by aligned, intrinsically asymmetric particles (e.g., dust)**
- **stellar magnetic fields**
- **scattering by asymmetrically distributed particles (e.g., a disk)**
- **asymmetric extinction of a symmetric source**
- **non-pointsymmetric geometry of a source**
- **reflections**

Polarimetry can infer quantitative details of the underlying physical conditions.

Substitute techniques are mostly marginal.

Polarization of <u>synchrotron and cyclotron radiation</u> is

- **due to relativistic electrons gyrating about magnetic field lines**
- **typically very high (up to 70%)**
- **a continuum effect**
- **not further detailed here**

Examples: SN remnants, pulsars, ISM, AGN jets, GRBs

Polarization mechanisms under consideration:

- cyclotron or synchrotron radiation ✓
- scattering by dust particles
- absorption by aligned intrinsically asymmetric particles (e.g., dust)
- magnetic fields
- scattering by asymmetrically distributed particles (e.g., a disk)
- asymmetric extinction of a symmetric source
- non-pointsymmetric geometry of a source
- reflections

Polarization due to dust, magnetic fields or scattering in asymmetric structures is

- **typically a 1% effect**
- **usually not related to the original emission process but is imprinted on the path from the source to the observer**
- **in many cases time dependent**

Meaningful observations require

- **LARGE telescopes**
- **stable instruments with precise calibration**

Effects of dust

Polarization by dust is

- basically a continuum effect
- therefore not elaborated on here

- can nevertheless not be escaped from because there is always foreground dust (often with P > 1 %)
- always adds information about the line-of-sight properties of the intervening dust grains: size, orientation, composition

Want to study dust properties at very high redshift; e.g., in AGNs or GRBs

Polarization mechanisms under consideration:

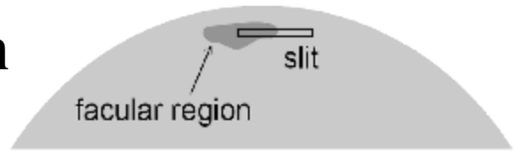
- scattering by dust particles ✓
- absorption by aligned intrinsically asymmetric particles (e.g., dust) ✓
- <u>magnetic fields</u>
- scattering by asymmetrically distributed particles (e.g., a disk)
- asymmetric extinction of a symmetric source
- non-pointsymmetric geometry of a source
- reflections

Magnetic observables

In magnetically sensitive spectral lines

- **magnetic fields cause Zeeman splitting**
- **the Zeeman components are polarized**
- **the polarization permits magnetic fields to be measured even in stars with unresolvable (e.g., due to pressure- or rotational broadening) Zeeman components.**

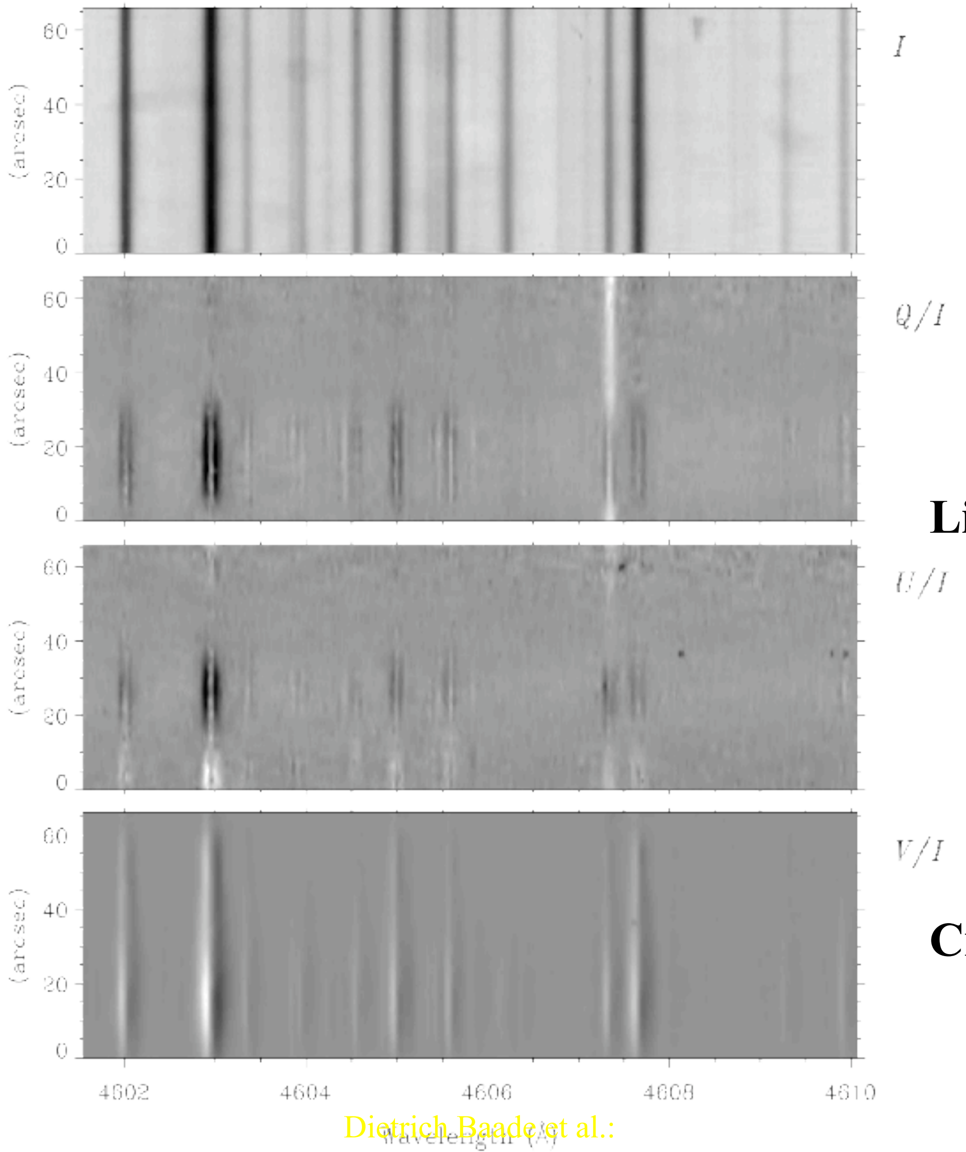
Sun



Flux spectrum

Transverse Zeeman effect – magnetic field lines perpendicular to line of sight

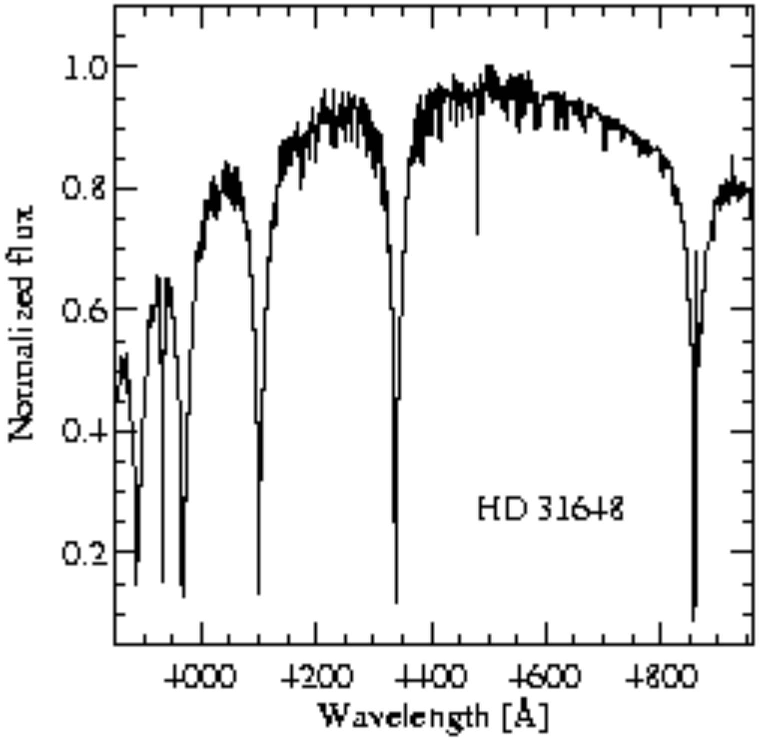
Longitudinal Zeeman effect – magnetic field lines along line of sight

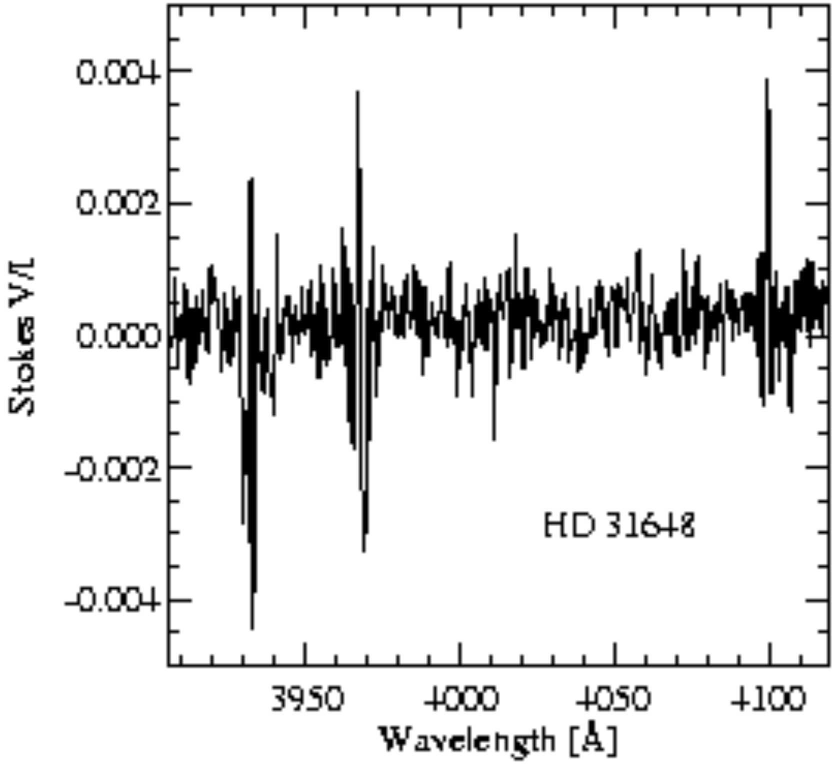


Linearly polarized

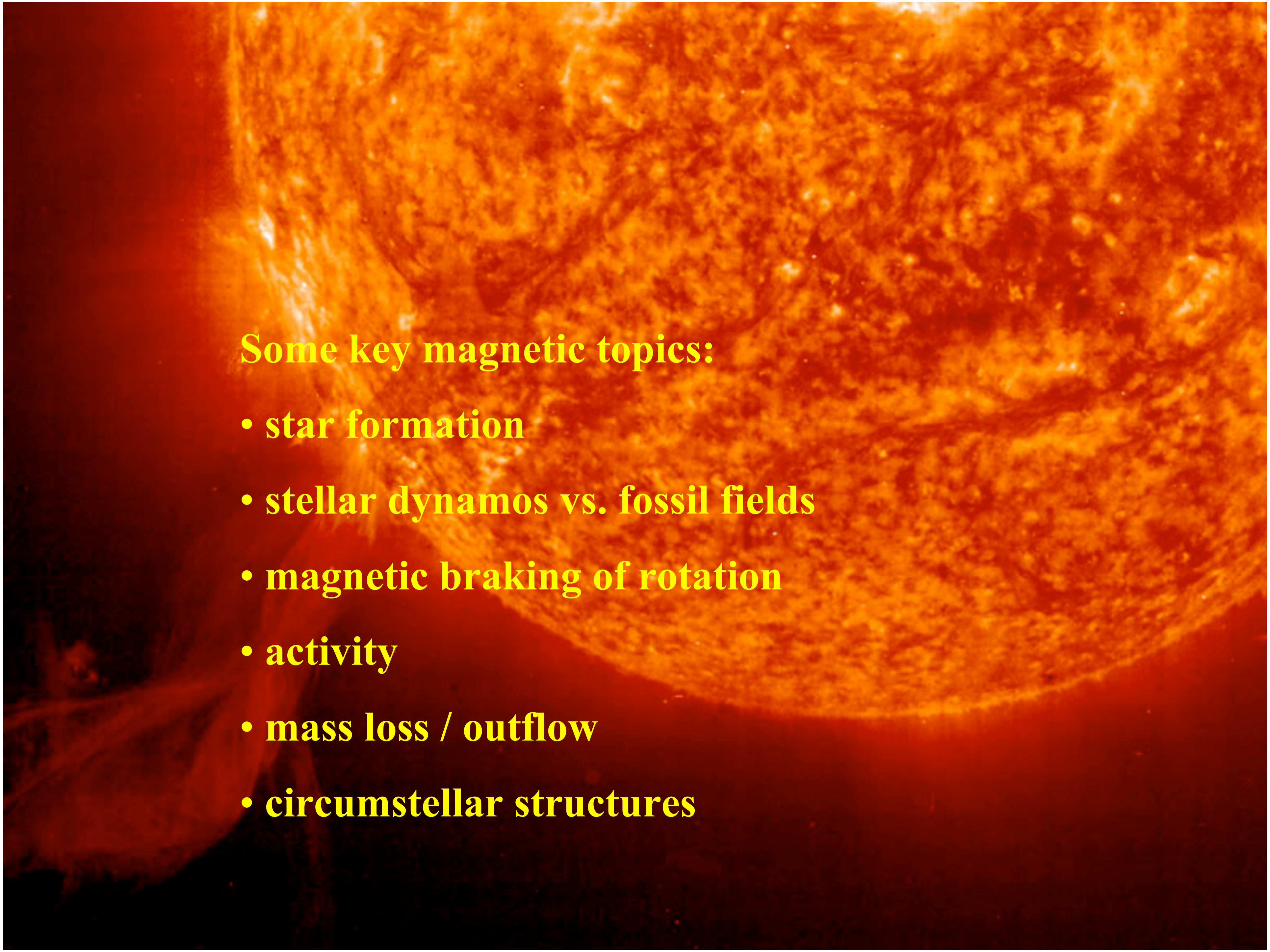
Circularly polarized


Examples of magnetic stars hotter than the Sun: helium-variable stars, Ap stars, HAeBe stars, white dwarfs, PNe, and many more
Plus most of the cooler stars





Polarization-boosted Zeeman effect in the Herbig Ae star HD 31648 (Hubrig et al. 2005)



Some key magnetic topics:

- **star formation**
- **stellar dynamos vs. fossil fields**
- **magnetic braking of rotation**
- **activity**
- **mass loss / outflow**
- **circumstellar structures**

Observational challenges associated with magnetic fields:

- **time dependency (rotation, activity)**
- **available equipment less sensitive than objects:**
  - **fields not yet measurable may still have visible effects**
- **higher-order and tangled field structures**
- **numbers of spectral lines**

Requirements: LARGE telescopes (high spectral resolution, high S/N), large instantaneous wavelength coverage, stability

Polarization mechanisms under consideration:

- magnetic fields ✓
- <u>scattering by asymmetrically distributed particles</u> (e.g., a disk)
- <u>asymmetric extinction of a symmetric source</u>
- <u>non-pointsymmetric geometry of a source</u>
- reflections

Polarization reminder

Any single photon is polarized.

In a pointsymmetric configuration, the polarization of every photon is cancelled by another one with the same axial distance but a position angle differing by ±90 degrees.

Any imbalance results in a net polarization.

The larger an elongation (asymmetry), the larger the polarization; rule of thumb:

1% polarization ~ 10% ellipticity

For a 1% effect, and aiming for an accuracy of < 1/10, need several 10^6 photons per resolution element

Polarimetry vs. interferometry (general)

If interferometry can be used: do it.

BUT: Interferometry requires the angular diameter of the source to match the length of the baseline.

Polarimetry possesses a linear - but relative - resolving power of order 2-3 of the overall scattering structure at:

- **any distance (photon limited only) and wavelength**
- **a negligible fraction of the cost of an interferometer**

Polarimetry vs. interferometry (E-ELT case)

Even in the optical (!), the resolution of the E-ELT will not be better than a few mas (with a challenging PSF).

Single-dish dilemma:

sensitivity ~ D^4 while resolution ~ D^1

- ▶ **For bright sources, VLTI is superior.**
- ▶ **For distant sources, D is too small (and there will be no ELTI or other alternative)**

Object	Linear Ø [Ø ☉]	Distance [pc]	Angular Ø [mas]
Sun	1	10	1
Betelgeuse	600	130	45
M2Iab star	600	50,000	10^{-2}
Ia SN at V_{max}	20,000	50,000	4
AGN (BLR)	$2\ 10^6$	$2\ 10^7$	1

Polarimetry vs. interferometry (II)

Even in the optical (!), the resolution of the E-ELT will not be better than a few mas (with a challenging PSF).

Single-dish dilemma:

sensitivity ~ D^4 while resolution ~ D^1

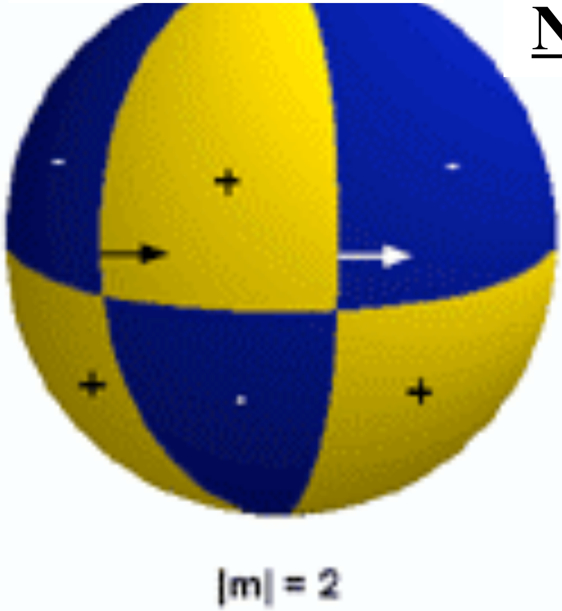
- ▶ For bright sources, VLTI is superior.
- ▶ For distant sources, D is too small (and there will be no ELTI or other alternative)

☻ In polarimetry, E-ELT can access 10,000 times larger
volume than the VLT can

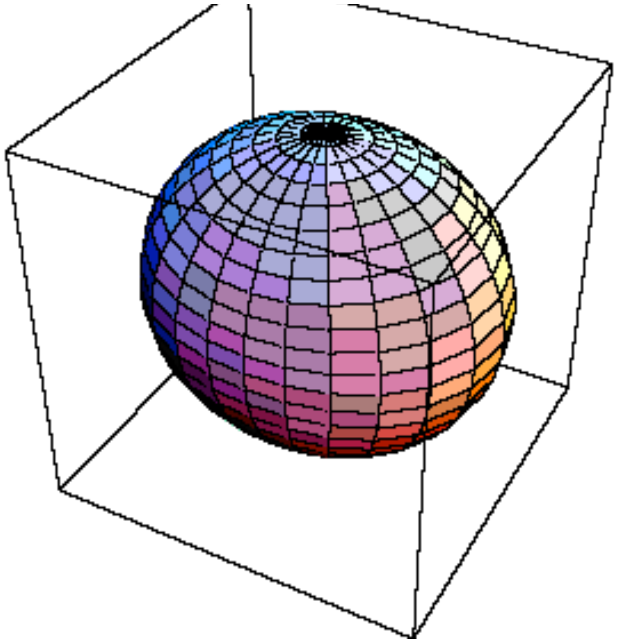
Examples of asymmetric scattering or extincting structures:

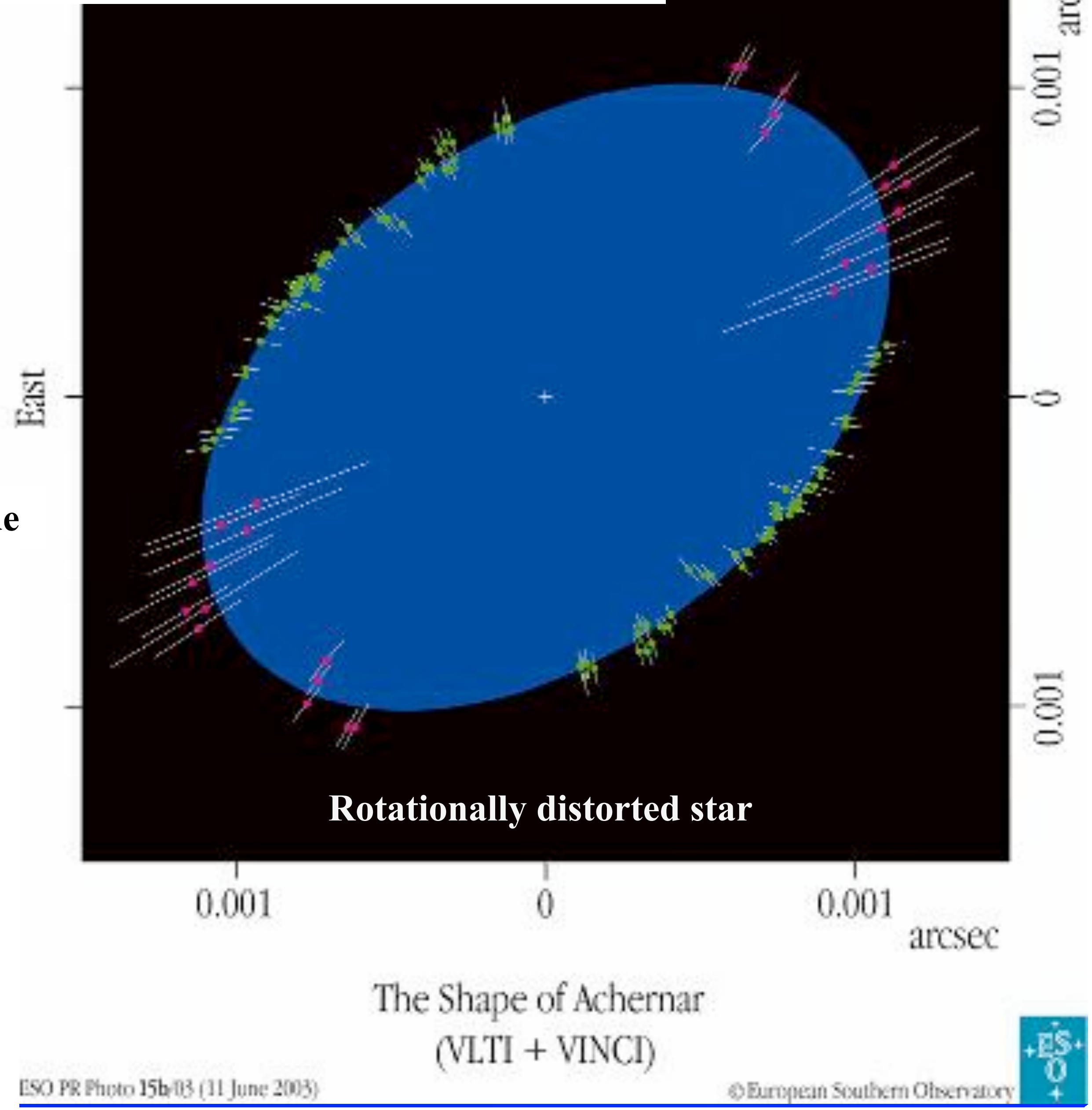
- binaries: orbital inclination; dense stellar winds (e.g., WR stars)
- accretion disks: orbital inclination in binaries; geometry; star formation; AGNs
- decretion disks (Be stars): geometry; position angle; formation and dissipation
- other outflows (incl. jets): YSOs, AGNs, Miras, PPNe, etc.
- eruptive and cataclysmic variables
- optically thick spots, clouds, or ejecta (asymmetric extinction)

Non-pointsymmetric sources



Example of nonradial pulsation mode





3-D resolution in multiple parameters

Spectro-polarimetry is particularly powerful when spectral lines permit zones with different dynamics, chemistry, excitation, etc. to be distinguished.

Additional differences in polarization can, for each of these zones, establish their own shape and orientation and so put them into one common 3-D perspective.

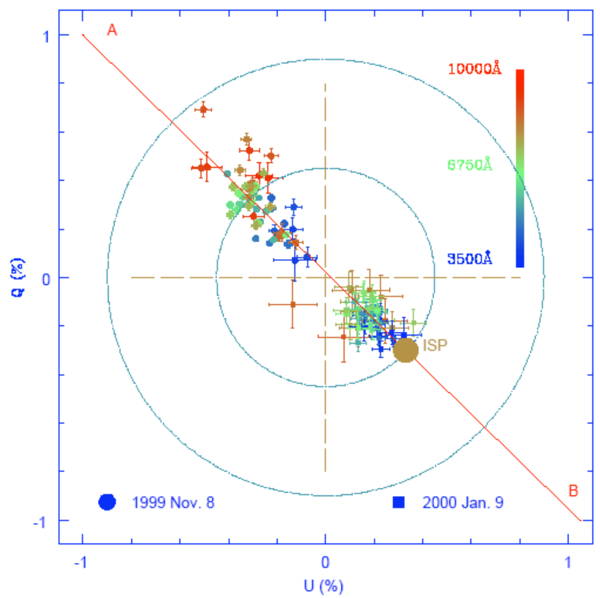
Spectropolarimetry is a tomographic tool.

Examples: core-collapse and thermo-nuclear (Type Ia) supernovae – time travels through exploding stars

<u>Core-collapse supernovae (I):</u>

- $M_{ZAMS} > \sim 8\ M_{\odot}$
- Degree of polarization <u>in</u>creases with time and, therefore, depth
- $\theta \sim$ const
- $P_{cont} < 3\%$

=> Asymmetric explosion



2000 Jan. 9 1999 Nov. 8

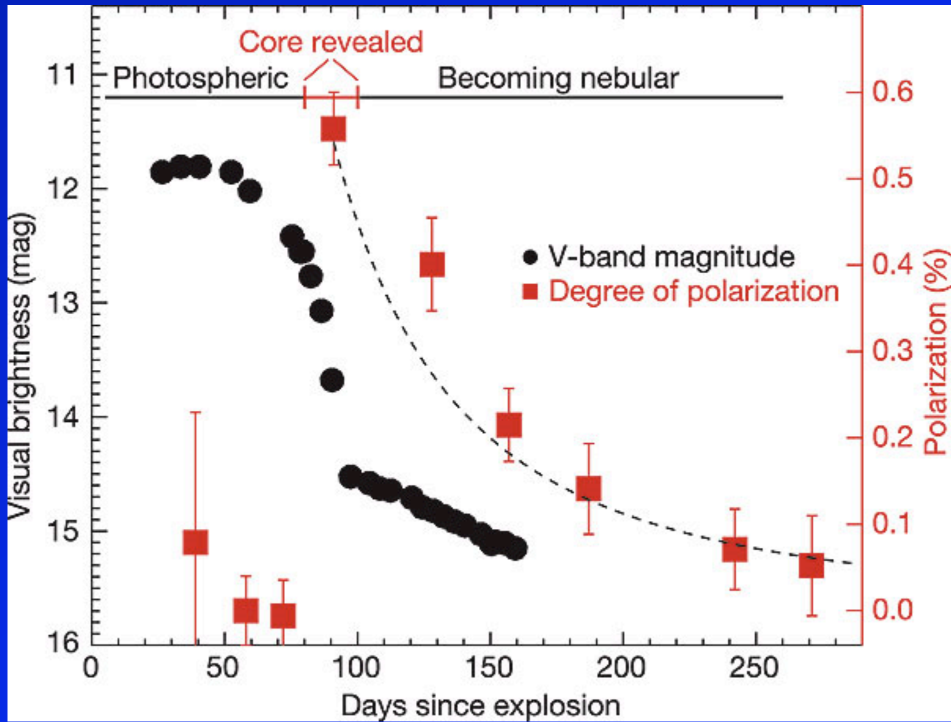
SN 1999em (Wang et al. 2001)

Core-collapse supernovae (II):

- **Early polarization the larger, the lower the envelope (hydrogen & helium) mass**

- **Polarization in Type IIp SN 2004dj jumped up when core became visible**

=> Explosion process itself is intrinsically asymmetric (jets? link to GRBs?)

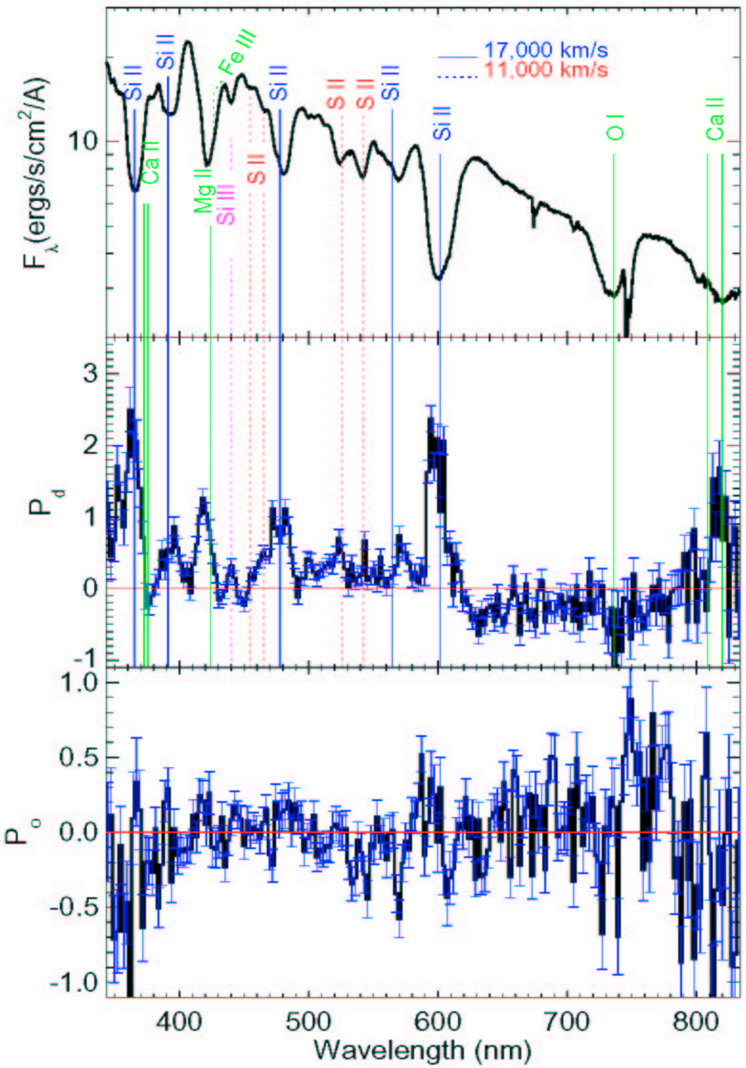


SN 2004dj (Leonard et al. 2006)

Type Ia supernovae:

- $M_{Ia} = M_{Chandrasekhar}$
- No remnants
- Degree of polarization decreases with time and vanishes ~ one week after maximum.
- $\theta \sim$ const
- $P_{cont} < 0.5$ %
- Δ V ~ 0.05 mag

Relevant for use as standard candles?

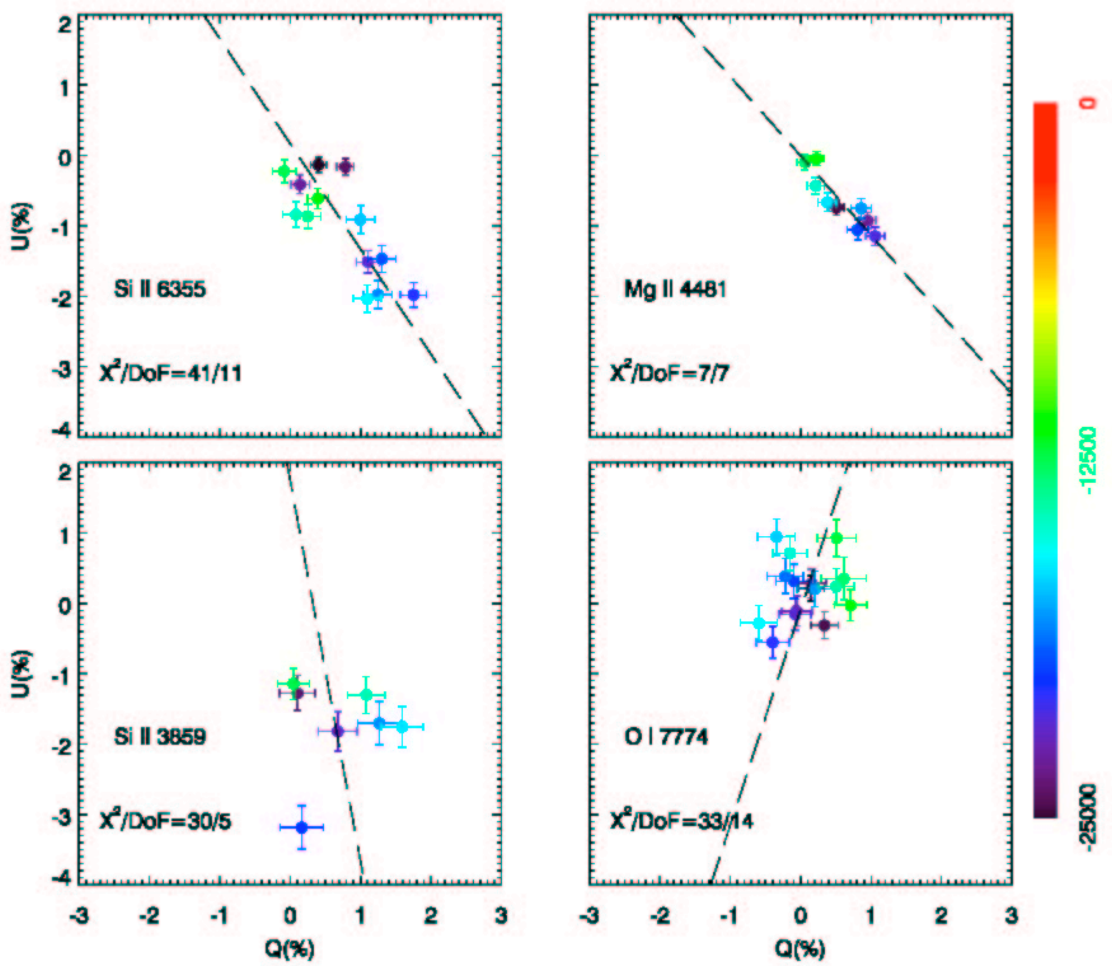


SN 2004dt >1 week before visual maximum (Wang et al. 2006)

Type Ia SN 2004dt:

CaII 3968, SiII 3859/6355, Mg II 4481, and OI 7774 all have about the same velocity profile, i.e. same radial distribution.

Yet, the OI line is at most marginally polarized while the polarization of the other lines is very high (up to 2%).



SN 2004dt >1 week before maximum (Wang et al. 2006)

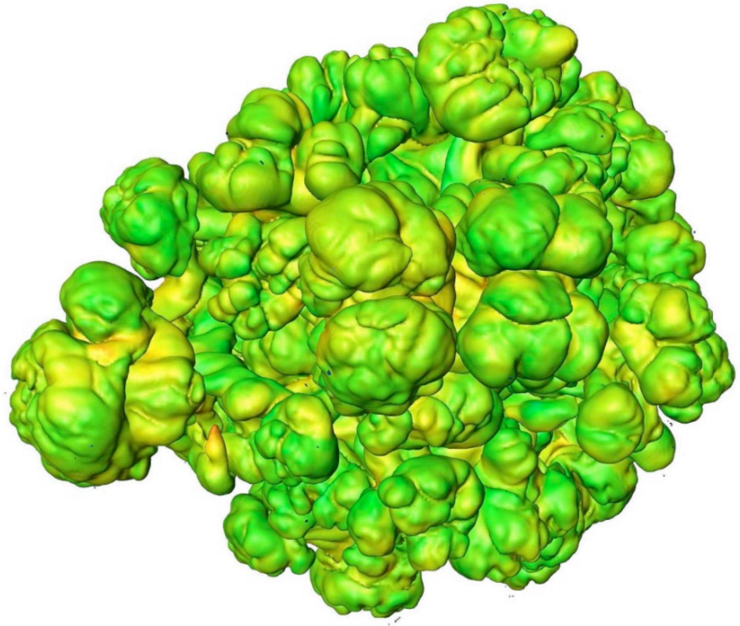
Symmetry of Type Ia supernova explosions

Other Type Ia SNe are similar.

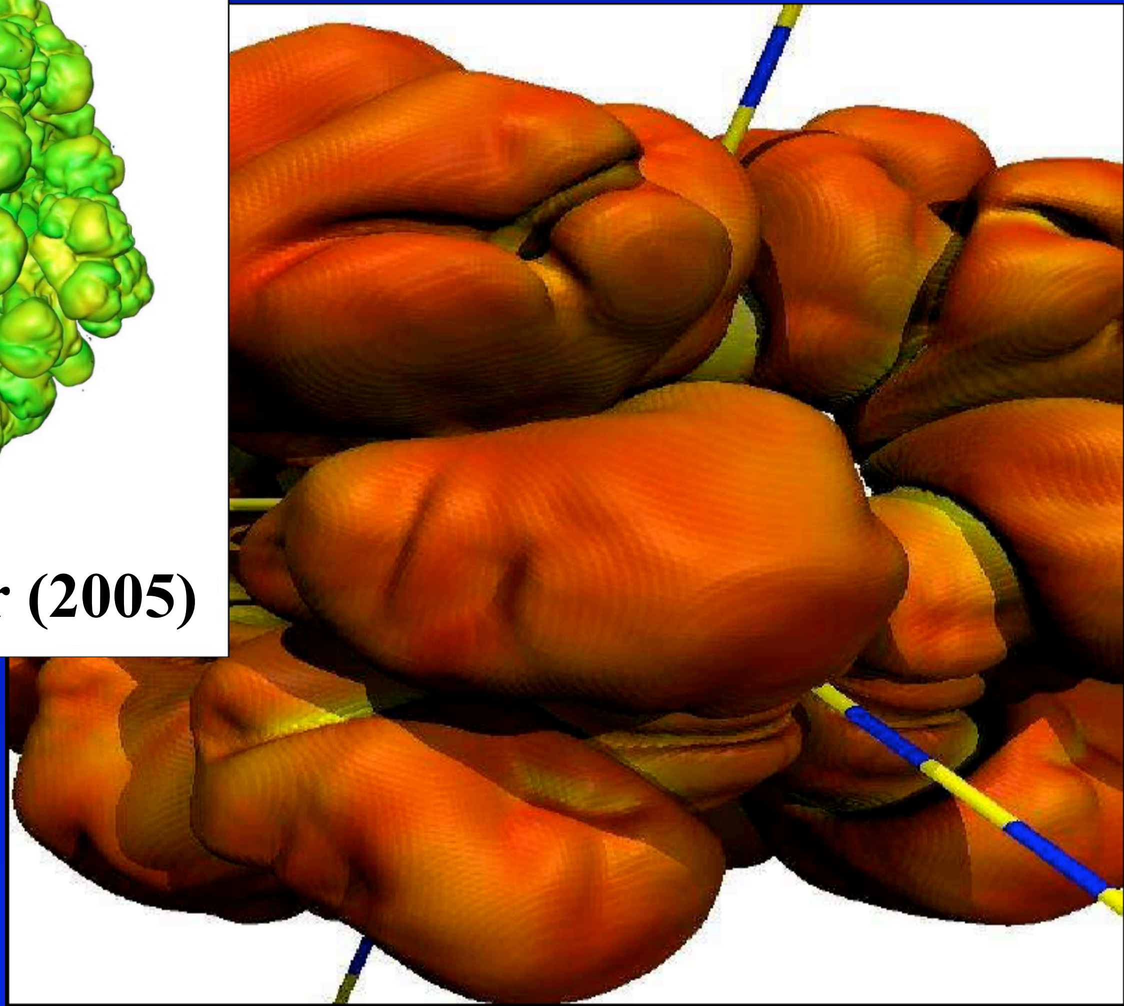
Without spectropolarimetry, the dichotomy between OI and other atomic species would not have been recognizable.

Curiously, there do not seem to be any unpolarized SNe Ia.

► Large-scale asymmetries that look about the same from all directions?



Schmidt & Niemeyer (2005)



Reinecke et al. (2002)

Type Ia SN explosion simulations at t < 1 s (!):

Asymmetric but about the same from all directions

Luminosity spread of Type Ia supernova explosions

Conceivably, details of the explosion process are slightly different from object to object.

Individual differences in intrinsic brightness could result.

Time-resolved spectropolarimetry could identify the differences between the explosions and provide individual corrections, also to redshift-based luminosities.

(For experts: detonation vs. deflagration)

This requires E̲LTs.

Polarization mechanisms under consideration:

- scattering by asymmetrically distributed particles (e.g., a disk) ✓
- asymmetric extinction of a symmetric source ✓
- non-pointsymmetric geometry of a source ✓
- <u>reflections</u>

Reflected or not reflected?

Polarimetry can separate reflected and directly received photons.

Example 1: Heavily obscured AGNs or LBVs

- **Self-luminous source in the core not directly observable.**
- **But light reflected off the envelope may reach the observer.**

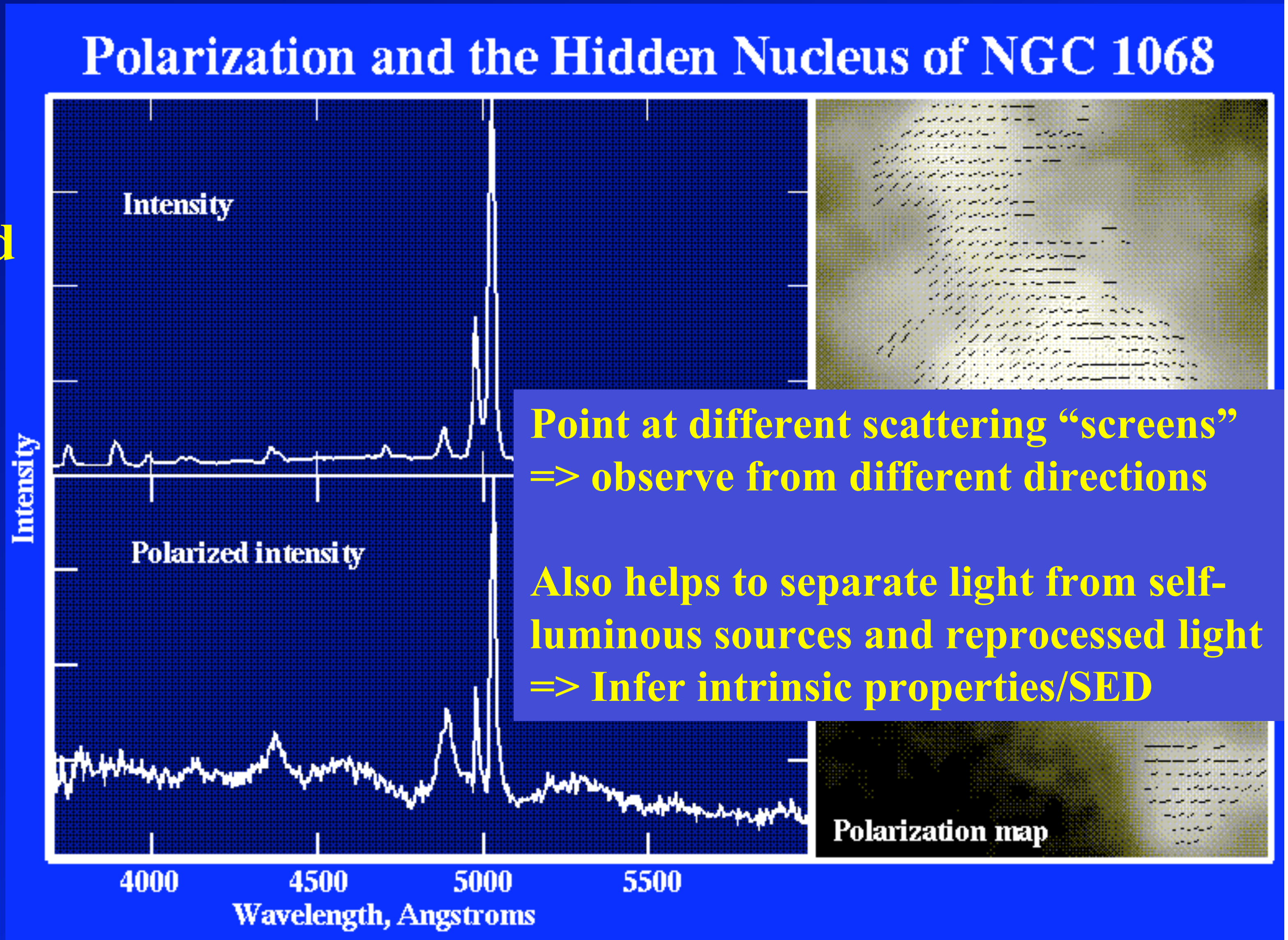
▶ Spectropolarimetry has <u>periscopic power</u>

Example 2: Extrasolar planets

- **Planets reflect a tiny fraction of their parent stars' light**

In integrated light:
Seifert 1

In polarized light:
Seifert 2



Point at different scattering “screens”
=> observe from different directions

Also helps to separate light from self-luminous sources and reprocessed light
=> Infer intrinsic properties/SED

Miller et al. 1991 Capetti et al. 1995

Punch lines (I)

(Spectro)polarimetry measures

- magnetic fields with synchrotron radiation
- stellar magnetic field strengths
- size, shape, and composition of dust particles
- weak reflected-light signatures not otherwise distinguishable against a very high background
- 3-dimensional shapes of point sources
  - independent of distance
  - separately for physically distinct regions
- formation of structure at very early epochs (AGNs, GRBs, dust grains)

Punch lines (II)

(Spectro)polarimetry

- **is often orthogonal to 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 %

- **can reduce throughput by < 10 % over broad ranges in λ**
- **requires, and optimally (D^4) exploits, high-D telescopes**

The E-ELT requires a (general-purpose) spectropolarimeter.