Fifty Years of Observations of Grw+70° 8247

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Among white dwarfs, Grw+70° 8247 stands as a particularly interesting object for various reasons. It is the first white dwarf in which a magnetic field was discovered. It is one of the stars with the longest rotation period (probably between 100 and 1000 yr). It shows one of the most unusual optical spectra ever seen because spectral lines are produced in presence of one of the strongest magnetic fields ever measured in the universe (~ 400 MG). Most importantly, this star has been the subject of a number of scientific articles co-authored by John Landstreet, from the one reporting the discovery of its magnetic field in 1970, to a very recent paper which presents new spectropolarimetric observations obtained from the William Herschel Telescope. Here I will show how the polarisation spectra of the star have changed during John's career, and what we have learnt from the observations of this star.

1 Introduction

This paper is part of the proceedings of a conference organised to celebrate a career that started with the publication of an article in ApJ in 1970 titled "Discovery of Circularly Polarized Light from a White Dwarf", by James Kemp, John Swedlund, John Landstreet & Roger Angel (Kemp et al., 1970). This paper was submitted to ApJ nearly exactly 49 years before this conference, and reported the discovery of circular polarisation from the white dwarf Greenwich +70° 8247[1]. This was the first discovery of a magnetic field in a degenerate star. Kemp et al. (1970) estimated in about 10 MG the mean longitudinal magnetic field (i.e., the component of the magnetic field along the line of sight, averaged over the stellar disk); we will see later that field strength was in fact underestimated by a factor of ~ 50.

Shortly before this paper, Preston (1970) had reported the results of a spectroscopic survey with the conclusion that few, if any white dwarfs, had a 1 MG magnetic field. Another paper by Angel & Landstreet (1970) had also reported the null results of a spectropolarimetric survey on nine white dwarfs (WDs). John explains elsewhere in these proceedings how the search for magnetic fields in WDs was motivated, and how, after the results of a first survey with null results, Grw+70° 8247 was picked up as a strong candidate magnetic star. Here I will just point out that the two papers, the one by Kemp et al. (1970) and the one by Angel & Landstreet (1970) mark the beginning of the polarimetric observations of WDs, and the beginning of the polarimetric exploration of magnetic fields in degenerate stars.

In this paper I will present a brief summary of the observations of Grw+70° 8247, and I will also show that fifty years after the discovery of the first magnetic WD, John is still one of the main contributors to the studies of degenerate stars. Just

[1]Simbad does not recognise the designation Grw+70° 8247; try AC+70 08247 instead.

enough to say that I am writing this introduction coming back from a 10 night shift at the WHT in La Palma during which John and I have continued to observe WDs with the ISIS instrument in spectropolarimetric mode, and one of our targets was again Grw+70° 8247.

2 The spectral appearance of white dwarfs

Before starting to present the observations of Grw+70° 8247, it is useful to remind ourselves what the spectra of the WDs usually look like. Therefore I will give a very basic introduction to the spectral classes of WDs as defined by Sion et al. (1983).

The spectral types of WD are designated by two or more letters, starting with the letter D, which means "Degenerate", followed by a capital letter, A, B, C, O, Q or Z, that reflects the presence of specific spectral features. After these two letters, a number may be added, which reflects the stellar temperature, defined by the ratio $50400/T_{\rm eff}$.

Most of WDs show only a single atom in their spectra, and this is due to the fact that gravitational diffusion leads to the lightest surviving element floating on everything else. DA stars have a hydrogen dominated atmosphere, and their spectra, if the star's temperature is higher than ~ 12000 K, show H lines. An example of a spectrum of a DA WD is given in the top-left panel of Fig. 1. Then there are WDs with He I lines only (spectral class DB – see top-right panel of Fig. 1). The letter C in DC stands for continuum and means that the spectrum is featureless (mid-left panel of Fig. 1). DO are hot WDs which show He II spectral lines (mid-right panel), and DQ stars show carbon features, either atomic or molecular (left-bottom panel). Finally, DZ stars exhibit metal lines only, with no H or He (right-bottom panel of Fig. 1). Due to gravitational settling, metals should sink below the photosphere on short time-scales, and their presence is explained in terms of ongoing accretion from a debris disk (Graham et al., 1990; Zuckerman et al., 2003). There are also various subclasses of WDs, and for their full definitions I refer to the original paper by Sion et al. (1983).

The intensity spectrum of Grw+70° 8247, shown in Fig. 2, clearly escapes all the previous classifications. It had been defined by Greenstein & Matthews (1957) as a "semi-DC" type with very little spectra structure having a shallow unidentified band at 4135 Å and two weaker bands at 3650 and 4475 Å, collectively known as "Minkowski bands". To understand the origin of these bands, we need to talk about magnetic fields.

3 The signatures of a magnetic field in the atmospheres of white dwarfs

The strength of the magnetic fields observed in different WDs spans almost five orders of magnitude, from 10^3 to 10^8 G. The process of line formation occurs at different physical regimes, and magnetic fields may be detected using different techniques. A quick and gentle introduction to these techniques is given, e.g., by Putney (1997).

Weak magnetic fields (up to a few tens of thousand Gauss) do not split the broad spectral lines of WDs, and may be detected only through the observations of the circular polarisation spectra. The left and mid panels of Fig. 3 show the example of spectra of a weakly magnetic DA star and of a DZ star, respectively. (In fact, the field

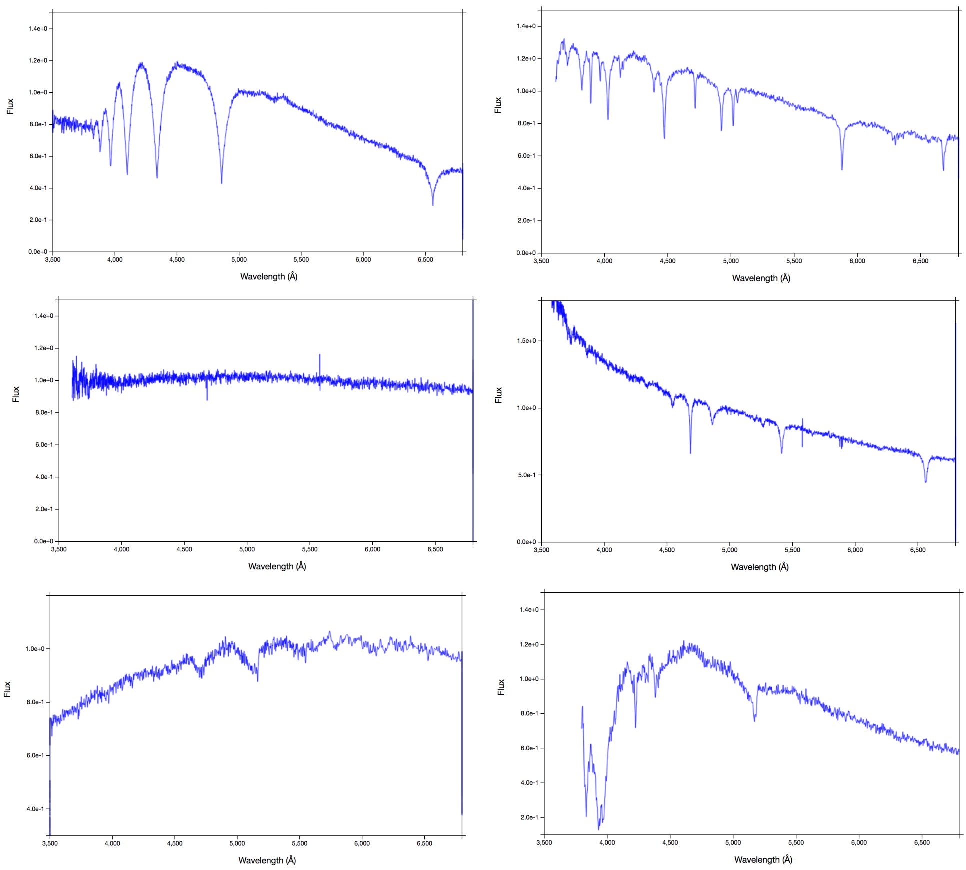

Fig. 1: Optical intensity spectra of DA star WD 1819+145 (top-left panel), DB star WD 1444−096 (top-right panel); DC star WD 1234+185 (mid left panel); DO star HD 018+2335 (mid-right panel); DQ star α CMi B (left-bottom panel); and of DZ star WD 2138−382 (bottom-right panel). Data from Giammichele et al. (2012), Bergeron et al. (2011) and from the SDSS, made available in graphical form by the Montreal White Dwarfs Database (MWDD) (`http://www.montrealwhitedwarfdatabase.org/`).

of the DA star WD 1105−340 is sufficiently strong that Zeeman splitting of Hα may be detected in high-resolution spectroscopy, but it escapes detection on higher-order Balmer lines observed at lower spectral resolution). Combining the information given by intensity and polarised spectra it is possible to measure the mean longitudinal magnetic field using simple analytical formulas that are derived under the so-called "weak-field" approximation. These formulas can be found in numerous articles (e.g., Eqs. (3) and (4) of Landstreet & Bagnulo, 2019b, and references therein).

When the magnetic field is strong enough to split spectral lines, one can measure the so-called mean field modulus, i.e., the magnetic field strength averaged over the stellar disk. The strength threshold may vary from 40 − 50 kG (for DA stars) to 200 − 300 kG (for DZ stars), depending on spectral type and instrument spectral resolution. An example is shown in the right panel of Fig. 3. Again, the field strength determination relies on the use of a simple analytical formula which shows that the

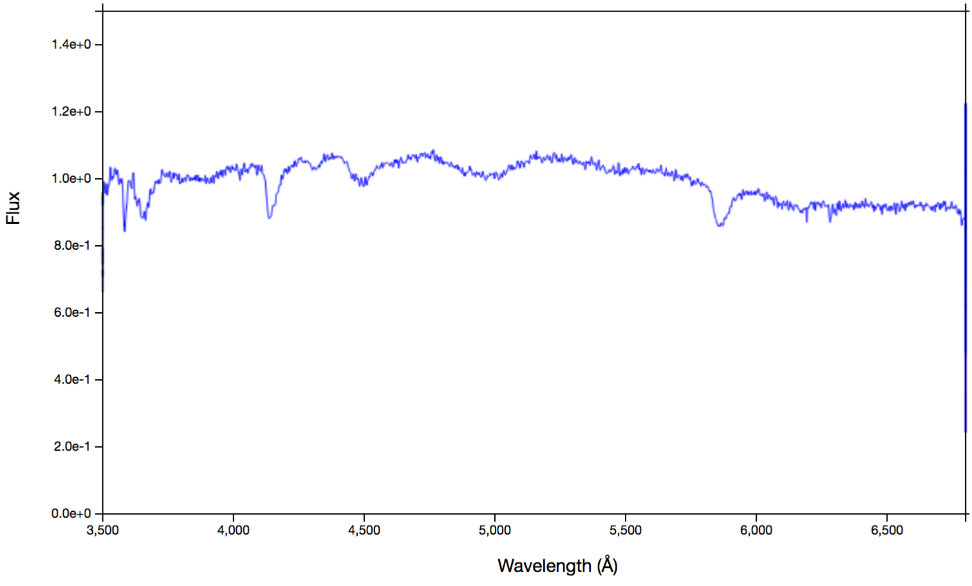

Fig. 2: Optical intensity spectrum of Grw+70° 8247. Data from Giammichele et al. (2012), made available in graphical form by the MWDD. Note that the band depths are typically 10 % or less.

magnetic field strength varies linearly with the Zeeman splitting (see Eqs. (1) and (2) of Landstreet & Bagnulo, 2019b).

As the field becomes stronger (say > 1 MG), we enter into the quadratic Zeeman regime, and numerical computations are needed to interpret line polarisation and splitting in terms of field strength, like those performed by Kemic (1974) for Hγ.

For magnetic fields stronger than 50 MG, magnetic and Coulomb forces are of comparable strength, and the various components of spectral lines shift by hundreds Å as a function of field strength. This situation is represented in the so-called "spaghetti diagrams", like those produced for hydrogen lines by Wunner et al. (1985) or Schimeczek & Wunner (2014). Because the magnetic field varies over the visible stellar disk, photons are absorbed in a large range of wavelengths, and spectral lines may be totally washed out, with very little or no contrast with the continuum. Practically, this means that the intensity spectrum of a strongly magnetic DA star may well appear similar to the spectrum of a non magnetic DC star. However, the components of the spectral lines may have stationary wavelengths, i.e, remain at approximately the same wavelength even for large changes of the magnetic field. For this reason, the spectrum of a magnetic WD may show broad and unusual absorption features, and this is what happens with Grw+70° 8247. This star is indeed a DA WD with a hydrogen-dominated atmosphere and hydrogen lines, with a magnetic field that reaches the strength of several hundred MG, capable of dramatically shifting all components of all spectral lines. Using energy level calculations by Praddaude (1972) and Roesner et al. (1984), Angel et al. (1985) identified various features of the spectrum of Grw+70° 8247 (see their Fig. 1). For instance, the feature at 4125 Å seen in the intensity spectrum of Grw+70° 8247 is in fact a σ component of Hβ

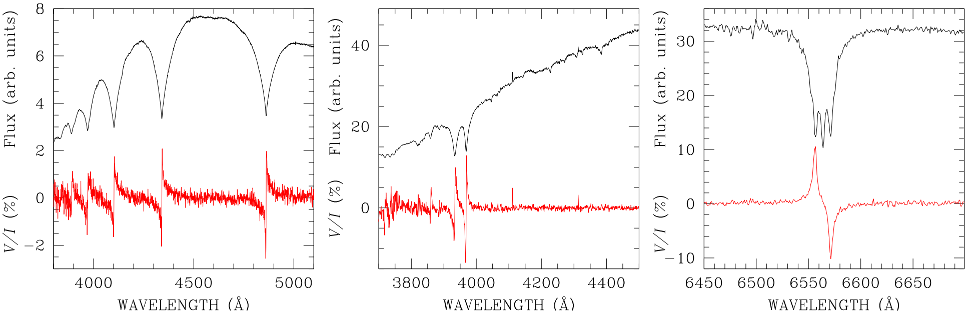

Fig. 3: Intensity and circularly polarised spectra of WD 1105−340 (left panel) WD 1009−184 (mid panel) and WD 0011−721 (right panel). The black solid lines show the intensity (not corrected for the instrument and atmospheric transmission function) and the red solid lines show the reduced Stokes parameter V/I. The observations of these stars have been presented by Landstreet & Bagnulo (2019b), Bagnulo & Landstreet (2019a) and Landstreet & Bagnulo (2019a).

shifted by the presence of a magnetic field with strength between 200 and 300 MG.

4 Spectropolarimetric observations of Grw+70° 8247

The circular polarisation measurements that were presented in the paper by Kemp et al. (1970) were obtained in broadband filters, but shortly after the discovery, the star was observed also spectropolarimetrically[2] (Angel et al., 1972; Landstreet & Angel, 1975). All observations obtained until the mid of the seventies failed to fimrly detect any kind of variability (both in linear and circular polarisation). After this period of intense observing activity, the conclusion was that the polarisation of the star was more or less constant, and subsequent works were mainly dedicated to theoretical interpretations rather than observing campaigns. A part from very few exceptions (e.g. Putney, 1995), Grw+70° 8247 was no longer spectropolarimetrically re-observed until this century at the William Herschel Telescope (WHT), using the ISIS instrument.

ISIS is a mid-resolution spectrograph equipped with polarimetric optics attached at the Cassegrain focus of the 4.2 m WHT with polarimetric capabilities in the continuum. With two arms, one optimised for the red part of the spectrum, and one for the blue part, ISIS allows one to simultaneously obtain spectra in a wavelength interval potentially spanning from ~ 3500 to ~ 10000 Å. Figure 4 shows ISIS+WHT observations in linear and circular polarisation of Grw+70° 8247 obtained in 2015 and in 2018 by Bagnulo & Landstreet (2019b). The top panel shows the intensity (non corrected for instrumental and atmospheric transmission). The second panel

[2]Incidentally, we note that the sign of circular polarisation appears sometimes changing in the literature, and the likely explanation is that different choices for its definition have been adopted. In this paper, Stokes V is given by the difference between right handed circular polarisation and the left handed circular polarisation, that are so defined: in a fixed point of space, the tip of the electric field vector carried by a beam having positive (negative) circular polarisation rotates clockwise (counterclockwise), as seen by an observer looking at the source of radiation. This is the most common definition among astronomers who study solar and stellar magnetic fields, but circular polarisation is often defined also in the oppositve way.

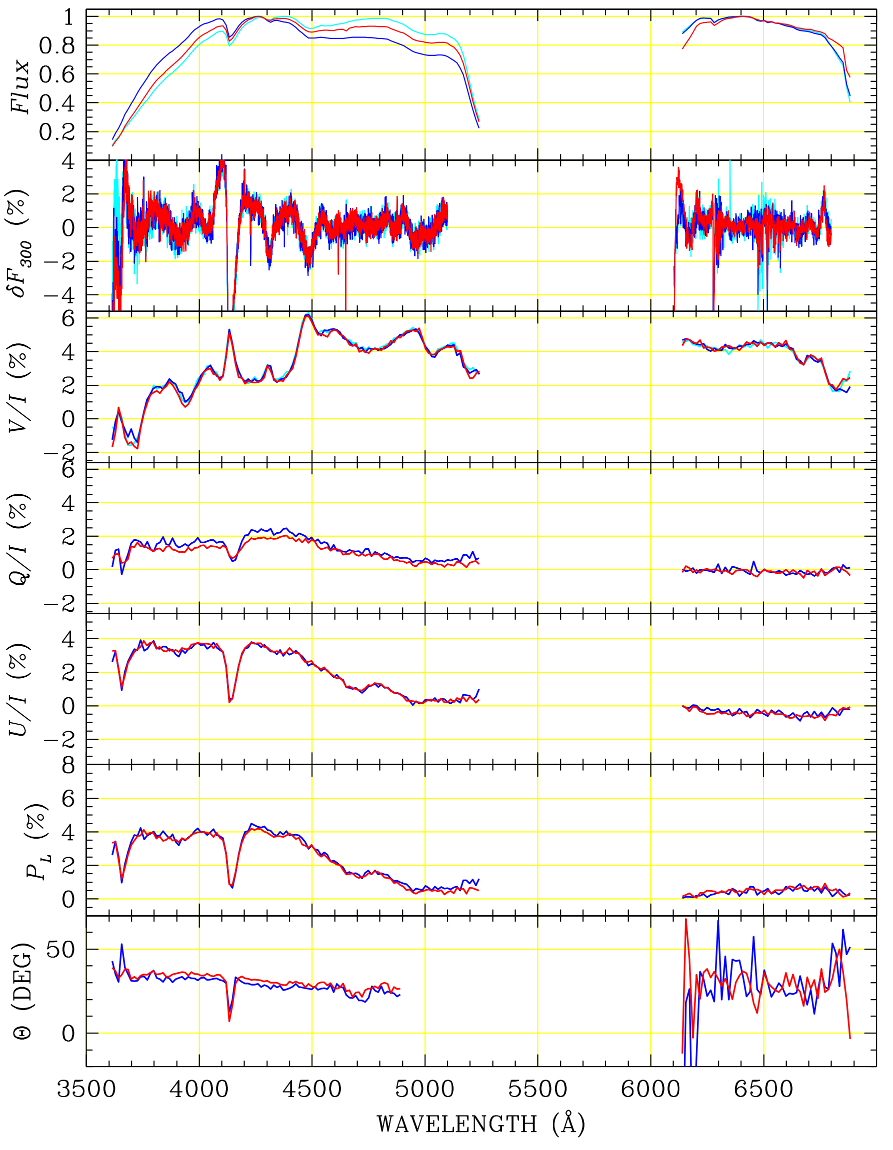

Fig. 4: Spectropolarimetric observations of Grw+70° 8247 obtained in 2015 and 2018 with the ISIS instrument of the WHT. From Bagnulo & Landstreet (2019b).

shows Stokes V/I, the third one Stokes Q/I and the fourth one Stokes U/I. Linear polarisation may be described either by the reduced Stokes parameters Q/I and U/I or by the fraction of linear polarisation $P_\mathrm{L} = \left[(Q/I)^2 + (U/I)^2\right]^{1/2}$ and its position angle Θ, such that $Q/I = P_\mathrm{L} \cos(2\Theta)$ and $U/I = P_\mathrm{L} \sin(2\Theta)$. The quantities P_L and Θ are shown in the fifth and sixth panels, respectively.

These observations, obtained three years apart, overlap well, confirming that the star is only slowly varying, if varies at all. However, comparing them with those published in previous literature, it is possible to establish whether the star has

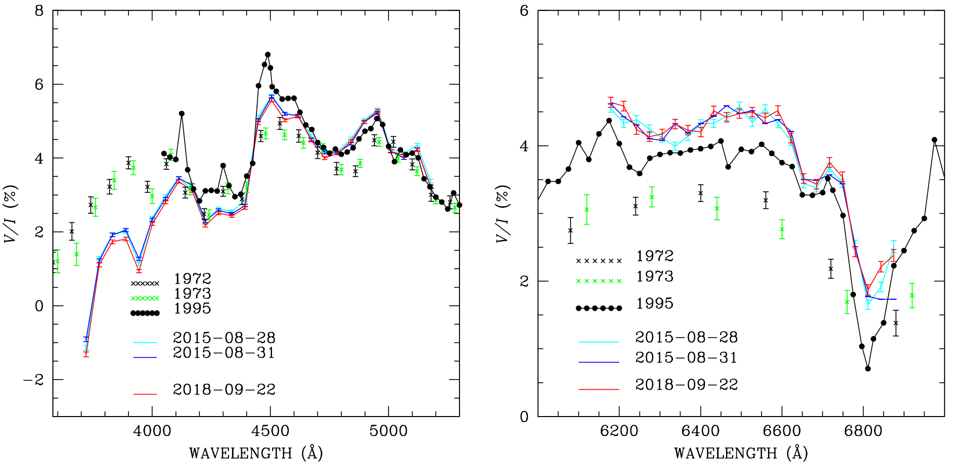

Fig. 5: Circular polarisation spectra presented by Landstreet & Angel (1975), Putney (1995) and Bagnulo & Landstreet (2019b). Note that the two panels have different scales.

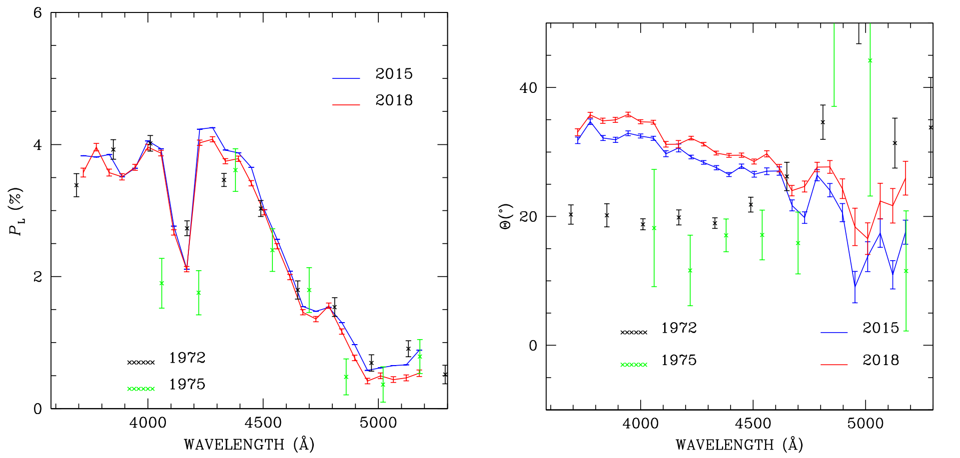

Fig. 6: Fraction of linear polarisation (left panel) and its position angle (right panel) as observed in 1972/1975 and in 2015/2019. Data from Angel et al. (1972), Landstreet & Angel (1975) and Bagnulo & Landstreet (2019b).

changed during a longer period of time.

Figure 5 shows circular spectropolarimetric observations obtained over almost fifty year interval. One can notice that there is evidence of a change in the circular polarisation. In the B and V regions of the spectrum, during the period 1975–1995, polarisation has increased, then it has decreased from 1995 to 2015 (left panel). At longer wavelengths circular polarisation has monotonically increased by $\sim 1\,\%$ (right panel).

While there is no strong evidence of a change of linear polarisation between 2015 and 2018, some differences are noticeable when comparing the most recent obser-

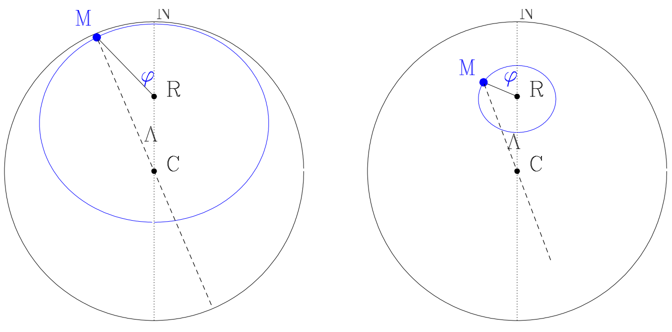

Fig. 7: Two examples of oblique rotator model. The figure is explained in the text.

vations with the earliest ones. The comparison is more meaningful if we represent linear polarisation with $P_{\rm L}$ and Θ rather than Q/I and U/I. It appears that during the last 50 years, the fraction of linear polarisation has changed very little, but its position angle has changed by about $10° - 15°$ in the blue (see Fig. 6). In the red part of the spectrum, the very low level of polarisation causes a large indetermination in the position angle. We make the assumption that the star may be represented in terms of the same oblique rotator model (Stibbs, 1950) adopted to explain the observations of magnetic fields in the chemically peculiar stars of the upper main sequence (Ap/Bp stars). Using this model, the position angle of the polarisation may be considered as a marker of the position angle of the projection of the magnetic axis on the plane of the sky (this would be exact in the weak-field Zeeman regime, see e.g. Landolfi et al., 1993). In Fig. 7 the black solid lines represent the stellar disc; the centre of the stellar disc C, the rotation pole R, and the North Celestial Pole N are aligned. M is the magnetic pole at the surface of the star, and the blue solid line represents its trajectory on the stellar disc as the star rotates, with ϕ representing the phase angle. The dashed line represents the projection of the dipolar axis in the plane of the sky, which forms an angle Λ with the reference direction to the North Celestial Pole. The left panel refers to a situation in which the angle β between dipole axis and rotation axis is larger than the tilt angle i between rotation axis and line of sight. As the star rotates, the position angle Λ spans monotonically the range $0° - 360°$, and the polarisation position angle spans twice the range $0° - 180°$. The right panel represents the situation $\beta < i$; as the star rotates, the position angle Λ spans a limited angle range, and changes direction twice, and so does the polarisation position angle. Under this very simplified model, assuming that the $10° - 15°$ variation of the position angle of the polarisation has been monotonic in the last 50 years, we can deduce that the rotation period of the star must be between a minimum of ~ 100 and a maximum of $\sim 1/2000$ years.

5 Conclusions

It is important to continue the spectropolarimetric monitoring of Grw$+70°\,8247$, with the ultimate goal to determine the rotation period and map the surface field structure. It is clear that the completion of this task is left to the future generations

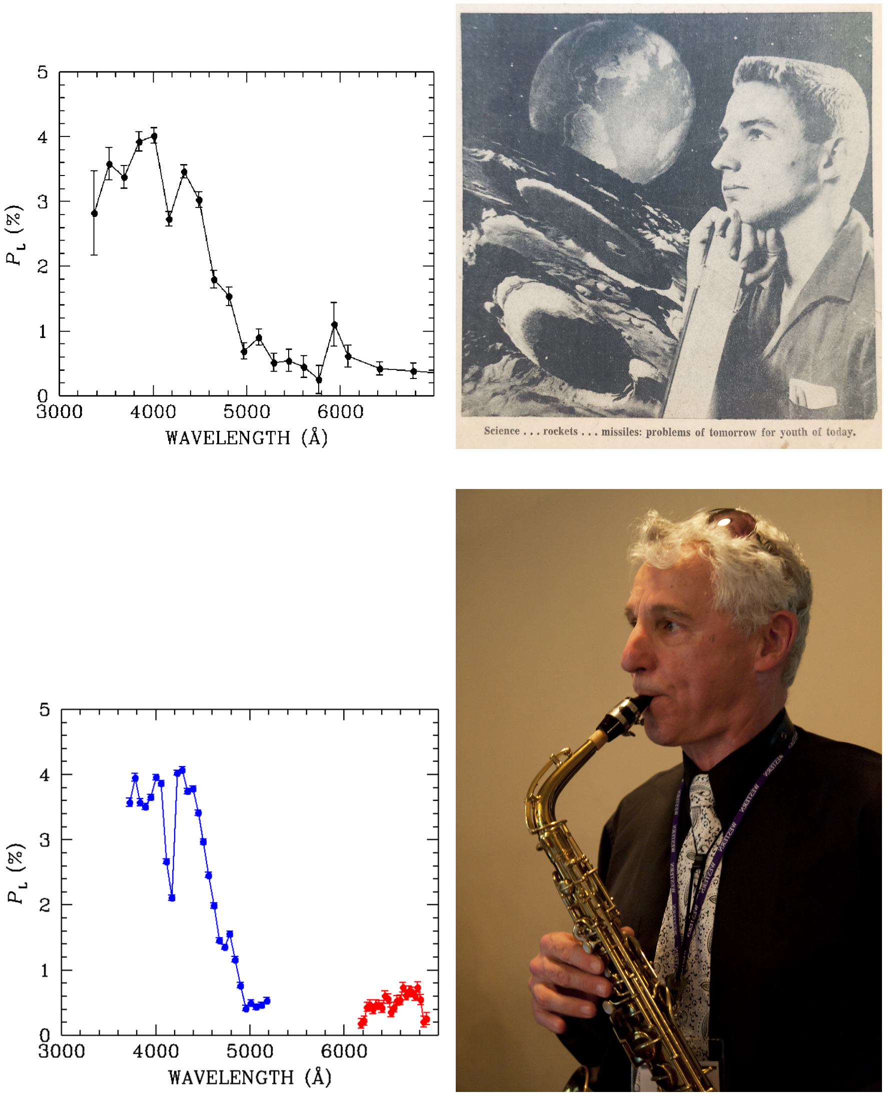

Fig. 8: Top panels: observations dated from 1970. Bottom panels: same observations obtained ~ 50 years later. Credit for the most recent photo of John: Stephanie Keating.

of astronomers.

Let me conclude by commenting that, as shown in Fig. 8, in the same way that the spectra of Grw+70° 8247 have not changed much in the last 50 years, neither has John.

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