Reflections on the discovery of the first magnetic white dwarf

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I was one of the six people most closely involved in the discovery of the first magnetic white dwarf in 1970, now 50 years ago. Thinking back on this event, I have realised that the discovery occurred when and how it did because of a series of lucky coincidences along a strange and winding path. In this paper I recount the events as I recall them, and reflect on how those unlikely coincidences helped us to succeed.

1 Background

In 1947, Horace Babcock announced the detection of a magnetic field on the surface of a main sequence A-type star \cite{Babcock1947}. This was the first detection of a field in any star other than that of the Sun, whose magnetic field had already been studied for some 30 years. This discovery aroused a lot of interest among astronomers. Almost immediately, P. M. S. Blackett proposed a theory suggesting that the magnetic moment of a planet or a star should be proportional to its angular momentum \cite{Blackett1947}. In particular, he suggested that strong magnetic fields might exist in white dwarf stars, which Blackett assumed would be very rapid rotators, although at the time nothing was actually known observationally about rotation rates of white dwarfs. Blackett discussed detection of stellar surface fields by the Zeeman effect, and he suggested that unidentified weak absorption features found in the star Grw+70° 8247 might be Zeeman patterns of Hγ and Hδ, broadened by a field of the order of 10\textsuperscript{7} Gauss.

By the early 1960s, Babcock and others had established that magnetic fields occur on the surfaces of members of a specific class of upper main sequence A and late B stars, the “peculiar A” (Ap) stars \cite{Babcock1958a}. These stars are in fact quite slow rotators, and so Blackett’s ideas fell out of favour.

The fields found in the Ap stars were shown to have strengths generally of the order of hundreds or thousands of Gauss, to vary periodically as the host star rotates and shows the field from different directions, but to display negligible secular change. The fields were found to be roughly dipolar in global structure. The various observed magnetic and related (spectrum and photometric variability) phenomena were satisfactorily unified and explained in the “oblique rotator” model \cite{Stibbs1950}.

However, the origin and nature of these static fields remained a puzzle. In the context of an effort to explain X-rays produced by the Crab Nebula, a radically different theory of occurrence of magnetic fields in stars was proposed by Lodewijk Woltjer, namely that magnetic flux might be roughly conserved during stellar evolution \cite{Woltjer1964}. Woltjer pointed out that the Crab might host one of the hypothetical neutron stars, and that such an object might possess a huge magnetic field.
Woltjer estimated the possible field strength from flux conservation, as

\[ B(R) \approx B_0 (R_0/R)^2 \approx (\rho/\rho_0)^{2/3} \]  

(1)

where \( R \) is the stellar radius, \( \rho \) is the mean stellar density, and 0 subscripts refer to the initial (or at least earlier) state. Assuming that the initial star had been a main sequence star with an internal field of \( B_0 \sim 10^4 \) G or so and a radius of about \( 10^6 \) km, which finally collapsed to a radius of order 10 km, the resulting neutron star might have a field of the order of \( 10^{14} \) G.

It was at this point that I entered the picture. I had arrived back in New York City at Columbia University in 1962 as a graduate student in the Physics Department. In March 1964, I started work on a thesis under the supervision of Woltjer, who had recently been appointed chair of the Columbia Astronomy Department. The basic premise of the thesis topic was an obvious extension of Woltjer’s idea about flux conservation. He pointed out that the same reasoning as for neutron stars suggested that there might be magnetic fields of the order of \( 10^8 \) G in some white dwarf stars, which are objects of \( R_{\text{wd}} \sim 10^4 \) km. My project was to try to understand how the presence of a field of this general size might affect energy loss from a cooling white dwarf.

I first tried to understand how a strong field might affect heat transfer through the white dwarf’s atmosphere and in the non-degenerate outer layers. I did not make a lot of progress in these directions, although I did realise that there could be “cyclotron opacity” under certain circumstances, and that this could lead to net circular polarisation of the emitted radiation. I also found that sufficiently strong fields could produce strong magneto-resistivity normal to the field in the degenerate white dwarf interior, but that the effects of this would probably only be detectable (in the form of obviously non-uniform surface temperature) for fields of, say, \( 10^9 \) G or more.

Then one of my Physics Department advisers, Gerald Feinberg, suggested that I try to estimate the enhanced rate of direct cooling of the interior of a highly magnetised white dwarf due to what we might call synchrotron radiation of neutrinos. This effect occurs when very occasionally the weak interaction leads to production (and immediate loss) of a neutrino-anti-neutrino pair in place of emission of a photon during synchrotron emission by an electron spiralling in a strong field. The question was to understand whether this could be a significant extra heat loss mechanism that could cause strongly magnetic white dwarfs to cool abnormally rapidly. It turns out that the effect does occur, but is unable to significantly affect the cooling of even very strongly magnetised white dwarfs. I submitted my thesis in August 1965, and successfully defended it the following January. I published the single paper from my thesis in the Physical Review \[ \text{[Landstreet 1967]} \], incidentally ensuring that it would not be seen by any significant fraction of the stellar physics community.

In the fall of 1965 I became an instructor at Mount Holyoke College, where I taught physics until the summer of 1967. As I had no significant community of collaborators or stimulators, I had some trouble finding my next astrophysics problem, but I did become interested in computing models of the evolution of stellar internal magnetic fields, and eventually also in modelling the observed surface fields of magnetic Ap stars. In the summer of 1967 I returned to New York as a post-doctoral fellow under my old boss Woltjer, just in time to be in close touch with the discovery of and some early work on pulsars.
2 Discovery

A few months after I returned to New York City, the first pulsars were discovered by Jocelyn Bell and announced by Hewish et al. (1968). Almost simultaneously, Woltjer’s friend Franco Pacini proposed that magnetised neutron stars could emit radio waves (Pacini, 1967). Further pulsars began to be discovered, and discussions were frequent among theorists interested in this phenomenon, including Woltjer. The consensus quickly formed that pulsars are rapidly rotating, very strongly magnetised neutron stars (Pacini & Salpeter, 1968; Pacini, 1968; Gold, 1968), a basic picture which has turned out to be essentially correct. As you can imagine, this was very exciting stuff for people interested in supernovae, neutron stars, and magnetic fields.

Sometime around this time, a physics professor at the University of Oregon, James Kemp, became interested in the polarisation of thermal radiation emitted by heated objects. He predicted, and observed in laboratory experiments that he carried out, that thermal radiation from heated metals (i.e. materials with free electrons) in a strong ambient magnetic field show broad band (continuum) circular polarisation of the order of $10^{-2}$% polarisation for a field of the order of $10^5$ G observed along the axis of the field (Kemp, 1970; Kemp et al., 1970a). The significance for our narrative of this apparently totally unrelated work will become clear later.

At the same time that this was going on, I had become very interested in the magnetic fields of the magnetic Ap main sequence stars. I was trying to build numerical models of the internal fields that could be evolved, and also trying to find a surface magnetic field distribution that would explain the variations of the mean line-of-sight magnetic field strength $\langle B_z \rangle$ that had been obtained by Babcock through the rotation cycle of a few Ap stars (Babcock, 1958b,a). This second quest put me in touch with George Preston, who had recently moved from Lick Observatory to the Hale Observatories in Los Angeles, and had begun a program of (photographic) polarised spectroscopy of magnetic Ap stars. Preston invited me to visit him in February 1969, and we found that we had a lot of interests in common. Preston loaned me some actual polarised spectra of real magnetic Ap stars, and effectively became my second mentor.

Then Woltjer made his second key contribution to the winding trail that led to the discovery of white dwarf magnetism. He had a discussion with Roger Angel, an Alfred P. Sloan Foundation Fellow in the Columbia Physics Department. Angel was a post-doctoral fellow working in the Columbia Radiation Lab on rocket experiments, and he wanted an unrelated project (one that did not depend on the success of a rocket launch) that he could work on in parallel with his rocket work. Woltjer suggested that Angel should try to discover a magnetic field in a white dwarf.

It was already clear, from the absence of obvious Zeeman splitting in the spectra of the more than one hundred white dwarfs with strong line spectra that had been observed spectroscopically at low resolution, mainly by Jesse Greenstein (Eggen et al., 1965, 1967), that fields larger than, say, 1 MG must be comparatively rare, so to find a magnetic white dwarf one would need to look for fields ten or more times weaker. This would require the development of a polarimeter to measure circular polarisation in the spectral lines of these faint (mostly fainter than $V \sim 12.5$) objects.

Angel accepted the challenge immediately, and during the spring and early summer of 1969 he designed and had the Physics Department shop build a portable
photoelectric filter polarimeter that, with interference filters, could be used to search for and measure the circular polarisation expected in the wings of the strong, broad Balmer lines, and that should be detectable even in fields of the order of $10^4 - 10^5$ G. As the local “expert” on white dwarfs (but completely ignorant of everything having to do with astronomical observing), I found myself swept into the project.

By midsummer the polarimeter was finished and ready for testing and use. It was a Cassegrain instrument, with a rapidly switched Pockels cell quarter waveplate followed by a Wollaston prism, tunable interference filters with 30 Å bandpass to isolate spectral line wings (the central wavelengths could be shifted to the blue by tilting the filters), and two photomultipliers, one for each output beam from the Wollaston prism. The basic quarter waveplate–Wollaston combination sorted the incoming light into two beams, each with intensity proportional to one of the two states of circular polarisation. The fast and slow axes of the Pockels cell were controlled by an applied high voltage, switched rapidly to allow each photomultiplier channel to measure the intensity of both polarisation states independently, using a pair of gated scalers for each channel. The instrument is described briefly by Angel & Landstreet (1970).

Angel arranged for two observing runs with the instrument at McDonald Observatory in Texas (by purchase, I think – time on the 82-inch was available at $450 per night, and at $750 on the 107-inch). We had about a week on the 36-inch in August, and a few nights on the 82-inch in September. During these runs Angel and I surveyed a total of nine bright DA white dwarfs. Such white dwarfs show only spectral lines of hydrogen, and because of the very high surface gravity of these stars ($g \sim 10^8$ cm s$^{-2}$) their Balmer lines have full widths of the order of 100–200 Å. We detected no polarisation in any of the white dwarfs we observed, but were able to put upper limits to possible line-of-sight fields of between $10^4$ and $10^5$ G (Angel & Landstreet, 1970). We almost immediately applied for more telescope time, this time at Kitt Peak National Observatory near Tucson, AZ. We were awarded 3 nights on the 84-inch and a week on a 36-inch telescope between June 26 and July 5, 1970.

In the meantime, two key events on our winding trail occurred. Sometime in autumn of 1969, George Preston made a visit to the Astronomy Department at Columbia University. I have a vague recollection that this visit lasted for a couple of weeks, but I am not sure. In any case, he heard all about the search that Angel and I were carrying out for magnetic white dwarfs. One consequence of the visit was that Preston realised that the fields in question (of the order of 1 MG) are large enough that, in hydrogen, the quadratic Zeeman effect leads to significant wavelength shifts that increase with increasing principal quantum number $n$ of the upper level, and so are larger for the higher members of the Balmer series. Preston was aware of a careful study by Greenstein & Trimble (1967) of radial velocities of white dwarfs using several Balmer lines in each star. He discussed the uncertainties of these measurements at length with Greenstein, and concluded that a field larger than about $5 \times 10^5$ G would have alerted Greenstein & Trimble to a problem with the measurements. Preston’s conclusion was that none of the 60-some WDs measured by Greenstein & Trimble has a magnetic field of more than about $5 \times 10^5$ G, and thus that searches for white dwarf fields by polarimetry needed to be sensitive to fields of order $10^5$ G or less.

But the most important consequence, for our narrative, of Preston’s interest in the magnetic fields of white dwarf stars occurred later that year, when he visited the
University of Oregon. He met James Kemp, the Oregon professor interested in the polarisation of thermal radiation whom I mentioned above. Kemp understood from his discussions with Preston that people were thinking of the possible occurrence of fields in (some) white dwarfs of the order of 1 MG, and that if such fields existed, detecting broadband circular polarisation could be a method of identifying these fields. Detecting the first MG field in a white dwarf would beautifully confirm the basic physical effect the Kemp had been studying, and would also be a very exciting discovery in its own right. Kemp immediately started work to adapt his laboratory polarimeter to measure the polarisation of starlight on the new 24-inch telescope of the university’s Pine Mountain Observatory, and soon began a programme of observation of the brightest (mostly DA) white dwarfs.

In early 1970, Kemp visited Columbia University, and he and I discussed his work and his search for broadband circular polarisation in white dwarfs. I explained to him that the programme that Angel and I were carrying out, using spectral lines, was a more sensitive method of detecting weak fields than his broad-band searches. However, I suggested that his method would be a very powerful way to search for large fields in DC white dwarfs. These are white dwarfs showing no spectral lines, and hence white dwarfs for which no a priori upper limits to magnetic fields existed from the absence of the Zeeman effect in normal flux spectra. I gave Kemp finding charts for several bright DC stars, and in particular I urged him to observe the very strange white dwarf Grw+70\(^{8247}\) in which the unique weak spectral absorption features (the “Minkowski bands”) were still completely unexplained, as this white dwarf seemed to me to be the most likely star to show Kemp’s predicted effect.

In June of 1970, Angel and I took Angel’s polarimeter to Kitt Peak Observatory to continue our searches for weak fields in DA stars. On June 30, Kemp called Angel to tell us that Kemp’s Pine Mountain polarimetric observations had twice detected a strong signal of circular polarisation in Grw+70\(^{8247}\). He asked us to confirm his result. We removed the narrow band filters from our polarimeter, replaced them with broadband glass filters, and observed Grw+70\(^{8247}\) that night. Our observations fully confirmed Kemp’s discovery of broadband circular polarisation.

Grw+70\(^{8247}\) thus became the first magnetic white dwarf ever discovered. Kemp initially estimated the field at roughly \(10^7\) G (we now know that the field is more nearly \(3 \times 10^8\) G). The event was sufficiently exciting that the Astrophysical Journal Letters put a news embargo on the paper (Kemp et al., 1970b) until it was published, as Science and Nature magazines often do for today’s hot new results. The discovery of the huge field of Grw+70\(^{8247}\) became a “new discovery” news item in both Science and Nature magazines, and even made it into the pages of Time Magazine.

3 Sequel

Angel and I followed up this exciting discovery vigourously. Armed with great first results, we were able to get more telescope time, and rather quickly found three more bright, circularly polarised magnetic white dwarfs: G195-19 (Angel & Landstreet, 1971b), G99-37 (Landstreet & Angel, 1971), and G99-47 (Angel & Landstreet, 1972). Kemp and his group also discovered another circularly polarised white dwarf, GD229 (Swedlund et al., 1974). All of these stars were discovered because of detectable continuum circular polarisation. It was only after several years that it was discovered that one of these stars, G99-47, actually shows normal
Zeeman splitting of Hα \cite{Liebert1975}. Zeeman splitting in flux spectra has, of course, been subsequently observed in numerous fainter white dwarfs.

Gradually, at a discovery rate of one or two new magnetic white dwarfs per year (up until about 2003, when the SDSS spectroscopic follow-up survey began to uncover tens and even hundreds of new magnetic white dwarfs with fields of 2–80 MG through Zeeman splitting), new fields were found, until now it is clear that 10% or more of white dwarfs have fields, with the distribution of fields covering the huge range of strengths from a couple of kG up to 1000 MG \cite{Landstreet2019}. Magnetism is now a well-established branch of white dwarf physics: see Stefano Bagnulo’s talk at this meeting.

The main point of this talk is that the discovery of the first magnetic white dwarf happened as a result of an (unlikely?) series of ideas and conversations. The initial possibility of finding MG fields was proposed by Blackett, and many years later by Lo Woltjer. Woltjer suggested to Roger Angel that a search for large fields should be initiated. Angel took up the challenge, quite incidentally including me in the project. Our search was initially unsuccessful, but (because of his interaction with Woltjer and me) George Preston heard about our search, and (improbably) passed the idea of MG fields in white dwarfs to physicist Jim Kemp at the University of Oregon, who decided to search for continuum polarisation in white dwarfs. He was also unsuccessful until he talked with me, and I explained to him that he should be looking at the DC stars, the one class of white dwarfs for which no strong prior upper limits on possible magnetic fields are known from optical spectroscopy. In particular, I urged Kemp to observe Grw+70°8247, which spectacularly displays the circular polarisation predicted by him. And so, finally, in 1970, the first magnetic white dwarf was found.

4 Postscript: why didn’t Jesse Greenstein discover the first magnetic white dwarf?

There is one further aspect of this story that is intereting to consider. We now know that magnetic fields occur in at least about 10% of white dwarfs \cite{Jordan2007,Kawka2014,Landstreet2019}. Spectroscopic observation of white dwarfs, particularly by Jesse Greenstein using the 200-inch telescope, was racing ahead \cite{Eggen1965,Eggen1967,Greenstein1969}; by 1970 more than 250 white dwarfs had been observed and classified spectroscopically at low resolving power ($R \sim 10^3$). It is interesting to ask why the first magnetic white dwarf was not discovered by observation of magnetic line splitting in the available optical spectra during the 1960s.

The answer is probably buried in the actual details of the instruments and their limitations. The 10% or more of white dwarfs with magnetic fields are now known to have fields ranging from a few kG to almost 1000 MG, a range in strength of 5 orders of magnitude, with the fields roughly uniformly distributed over this full range at a rate of perhaps 2 or 3% occurrence per dex of field strength. Now in fact the magnetic line splitting due to a magnetic field is only really obvious in low resolution spectra for field strengths above about 2 MG, and fields above about 20 MG lead to spectra that, due to the different shifts of the many sublevels of each level of H, are sufficiently complex to be quite difficult to interpret, if indeed the many weak lines were detected at all. So the first obstacle was that in practice only about a fifth
of the possible fields might have been easily recognised by a spectroscopist. This reduces the probability of finding a visibly magnetic white dwarf to roughly 2 or 3% of a sample.

But there were still further difficulties. Of the presently known magnetic white dwarfs, only about 25 or 30 are brighter than $V = 15$ (and thus could be observed during the 1960s with relatively high $S/N$). Only two of these brightest magnetic white dwarfs, G99-47 and Feige 7, have fields in the range easily detected by visual inspection of optical spectra. Both were in fact observed by Greenstein, who classified both as DC white dwarfs, in one case because the only visible spectral line lies outside the blue spectral window used for almost all spectroscopy during the 1960s, and in the other case because the numerous weak blue spectral lines simply were not obvious in the low $S/N$ spectrum.

In contrast, fields large enough to generate an easily detected circular polarisation signal of, say, $V/I \approx 0.5\%$ are present in perhaps 5% of white dwarfs. Furthermore, the use of photoelectric detectors, with their far higher detective quantum efficiency compared to the photographic and image tube technology used for spectroscopy during the 1960s, together with the fact that the full optical spectrum contributes to massively increase the $S/N$ of the single polarimetric broad-band observation, meant that searches for circularly polarised white dwarfs could be carried out relatively rapidly even on telescopes considerably smaller than the 200-inch. The first white dwarf field, after all, was discovered using a 24-inch telescope and confirmed on a 36-inch telescope (Kemp et al., 1970b). Kemp’s new broadband circular polarimetric search method, combined with the enormous increase in overall spectral efficiency due to multiplexing and greatly increased detective quantum efficiency compared to spectroscopy, turned out to be the best available search method before the arrival of CCD spectroscopy.

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