Magnetic fields in main sequence stars and white dwarfs: challenges for the twenty-first century

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1. Introduction

I have been invited by Iosif Romanyuk to give an opening talk on the rather general topic of what we have learned about magnetic fields in stars during the present century, and what particular challenges and problems we may want to work on in the coming one. In other words, my topic is "where have we been, and where are we going?". Because this is not really a normal scientific paper, I will take the liberty of treating it rather informally.

Let me start by saying that I am honoured to have been invited to give this introductory lecture at the last meeting devoted to stellar magnetic fields of the 20th century. It is also a great pleasure to see here a large number of friends and colleagues who share my interests in this subject. And last — but not least — I should mention that I am extremely impressed with the obvious high level of scientific activity and achievement here at the Special Astrophysical Observatory, which is all the more remarkable considering the very difficult situation in Russia today. It is clear that this meeting will be scientifically very productive, and I am delighted to be here.

I would like to start my talk by reviewing in a very general way some of the main discoveries and developments in the field of stellar magnetism (mostly in fossil magnetism, since that is the main focus of the meeting) that have occurred during this century. From this survey, we can gain a sense of just how much our predecessors and we have actually accomplished — and it is a rather impressive inventory. I next want to look briefly at some of the main areas of activity today — these are the topics that will be the main areas of discussion at this meeting — and then finally set out some significant goals for us to achieve, and problems for us to solve, in the next century.

2. Important discoveries and developments in this century

Just to confuse the issue, I would like to start the 20th century off a little early, because two particular discoveries of great importance to this meeting missed being in our century by a few years. Perhaps we can consider them to be "honorary" 20th century discoveries, because they have been so central to our

- The first *white dwarf* was discovered by the American telescope maker Alvan Clark in 1862, when he observed Sirius to test the quality of one of his telescope lenses and saw for the first time the very faint light of Bessel's "dark star", almost invisible in the glare of the brilliant primary star.
- One of the first great spectral classifiers, Antonia Maury, reported the discovery of *spectral peculiarity* in the spectra of a number of bright middle main sequence stars in the *Harvard Annals* for 1897. Among the peculiar stars she noticed are a number that have since been intensely studied by many of us. Her list included α^2 CVn, β CrB, θ Aur, ϵ UMa, γ Ari, and ϕ Dra among the magnetic Ap's, as well as the HgMn Ap stars α And and μ Lep.

These two discoveries, of the two main types of stars which are the principal focus of this meeting, set the stage for the important discoveries and advances of the present century. Several more basic discoveries followed soon after:

- In 1906 Hans Ludendorff, at Potsdam, reported that some of the spectral lines in the peculiar star α^2 CVn vary in intensity.
- The very first stellar magnetic field was discovered in 1908. George Ellery Hale, using the new 20-m solar tower at Mount Wilson, discovered that spectral lines in sunspots are split and polarized by the Zeeman effect, which had been observed in the laboratory only a decade earlier by Pieter Zeeman. Although this discovery is fundamental to all of solar activity, we are still far from having worked out many of its consequences.
- In 1913, Aristarkh Belopol'skii at Pulkovo made an extremely important discovery. He showed that the Eu II line at 4129 Å in α^2 CVn varies *periodically* in intensity, with a period of 5.5 days. He also suggested, as a possible explanation of this phenomenon, the idea that the star is surrounded by some kind of cloud or ring with a condensation in one area — a clear forerunner of the oblique rotator model. The following year, Paul Guthnick and Richard Prager of Berlin reported the small light variations of the same star using the newly developed photoelectric cell.

During the following four decades, much was learned about the nature of stars, both on the main sequence and as white dwarfs. In solar physics, the study of the Sun's magnetism opened whole new areas of research. Spectrum variability was observed in a number of peculiar A stars (for example in CS Vir and 73 Dra by W. W. Morgan during the 1930's). But the next major steps in the study of magnetism in other stars were only taken after the end of the Second World War.

- In 1945, Thomas Cowling, of the University of Leeds, discovered that a stellar magnetic field, once established in a star, would decay so slowly (due to the high electrical conductivity and huge size of the star) that any contemporary field could be the remnant of one established in the star billions of years earlier. He thus initiated the idea of "fossil" magnetic fields, one of the central theoretical ideas about stellar magnetism, before magnetism had even been discovered in any other star than the Sun.
- The following year, Horace Babcock, using the high dispersion spectrograph of the 2.5-m telescope at Mount Wilson with a polarization analyzer, observed Zeeman splitting in the spectral lines of the Ap star 78 Vir. He quickly followed this discovery with the detection of magnetic fields in a number of other Ap stars, including γ Equ, α^2 CVn, CSVir, β CrB, HD 10783, HD 153882, and HD 188041. By 1950 he was able to report that the observed longitudinal component of the field of CSVir varies periodically with the same period already determined for the spectrum variability of this star by Armin Deutsch at Mount Wilson.
- By 1950, Babcock's observations were being interpreted by theorists with models ranging from magnetic oscillations and waves to giant sunspots. Among the proposals was the oblique dipole rotator model, developed independently by British astronomer D. W. N. Stibbs and by Babcock (although it took some years before Babcock fully accepted this model). This idea has become the fundamental phenomenological model underlying almost all work on the magnetic field structure of magnetic Ap stars and magnetic white dwarfs.
- A major new field of stellar magnetism opened in 1967 with the discovery of pulsars by Jocelyn Bell and Anthony Hewish of Cambridge University. These bizarre radio sources turned out to be neutron stars with magnetic fields of order 10^{12} G; the Cambridge radio astronomers' discoveries were the forerunner of some hundreds of pulsars now known.
- In 1970, a magnetic field of strength intermediate between the 10^3 G of main sequence stars and the 10^{12} G fields of neutron stars was detected in the white dwarf Grw +70° 8247 by James Kemp, John Swedlund, Roger Angel and me. This discovery has now led to the detection of megagauss (or larger!) fields in some 50 white dwarfs.

- Also in 1970 Georges Michaud proposed what has turned out to be the principal sorting mechanism that leads to the abundance peculiarities on magnetic Ap stars. Michaud showed that the competition between gravitational settling and radiative levitation of trace heavy elements in a reasonably stable stellar envelope could lead to abundance anomalies qualitatively like those observed in many of the peculiar stars of the middle main sequence.

- Another major breakthrough in our ability to explore the magnetic Ap stars came in 1978 when Don Kurtz, working at the Sutherland Observatory of the University of Cape Town, discovered multi-periodic, non-radial, high overtone pulsations in the magnetic Ap star HD 101065 (Przybylski's star). This discovery, followed by the detection of similar pulsations in other cool Ap's, will eventually provide us with a powerful means of probing the interior structure of magnetic stars.

- An interesting extension of the known domain of main sequence magnetism towards hotter, more massive stars came with the discovery by Ermanno Borra and me of magnetic fields in some early B He-strong stars. We were able to show that the first such star found to be magnetic (in 1977), σ Ori E, not only has a strong field, but also supports some kind of co-rotating, magnetically confined circumstellar envelope which is dense enough to cause weak eclipses and shell lines at certain rotational phases. (This structure is remarkably similar to the cloud or ring with condensations proposed by Belopol'skii more than 60 years earlier!)

- A couple of years later, in 1980, another important extension of the known domain of magnetic stars occurred with the discovery by Richard Robinson, Pete Worden, and Jack Harvey of detectable Zeeman broadening of spectral lines in two main sequence stars cooler than the Sun. It had of course long been expected that some solar-type stars would have substantial surface magnetic fields, but the complex nature of these fields (based on the solar analogy) meant that the usual method of detecting fields in magnetic Ap stars could not be applied.

- And finally, to complete this list of interesting discoveries and developments, I mention the detection of radio emission from hot Ap stars, first found by Stephen Drake, David Abbott, and a number of collaborators in 1985. The detected radio emission, found in σ Ori E and in HD 215441 (Babcock's star) among others, apparently comes from relativistic electrons trapped in a stellar magnetosphere.

3. Major ongoing lines of research

The numerous discoveries and developments I mention above, and others, equally important, that I have omitted, have led in turn to many ongoing lines of research as we try to find more examples of interesting types of stars, to discover further new phenomena, and to explore the consequences of theoretical ideas. These continuing research projects, though perhaps not as exciting as the initial discoveries and theoretical breakthroughs, are every bit as important as we try to understand fully the physics behind the phenomena we observe.

Some of these lines of research have become so large that one could almost speak of major multinational industries developing. Many of us are involved in one or more of these industries, and they will certainly continue into the next century, to be carried on by the younger generation. Several of the major research fields at present are the following ones:

• Hale's discovery of sunspot fields led eventually to an international effort to observe all aspects of solar activity that are governed and/or energized by the magnetic fields. The set of phenomena observed and modelled has now grown to include the chromosphere, corona, solar wind, sunspots, plages, filaments, prominences, and flares. All of these phenomena are essentially affected by the complex solar magnetic field. Their elucidation has turned out to constitute an enormously tough set of interlocked problems. This field of research has commanded the attention of numerous major observatories, including (at present) the Crimean Astrophysical Observatory, the US National Solar Observatories at Kitt Peak and Sacramento Peak, Big Bear Solar Observatory, the Themis telescope at the Observatory of the Canaries, etc.

In recent years this field has branched out into the observation and analysis of magnetic fields in solar-type stars. Fields of strengths of 2 or 3 kG are now known in well over a dozen stars; in various stars they appear to cover anywhere from 2% to 70% of the stellar surface. Jean-Francois Donati, Nicolai Piskunov, John Rice, and Klaus Strassmeier, among others, have been active in developing mapping methods for such solar-type stars.

• Similarly, Babcock's discovery of magnetism in Ap stars has led to a large international observing effort, both to measure the magnetic fields of these stars and to study their many other peculiarities (such as their very bizarre surface chemical abundance patterns, their spottiness, the pulsations exhibited by some, and even their radio emission). Groups that have contributed to this work include George Preston at Mount Wilson and Las Campanas Observatory, and Sidney Wolff at the University of Hawaii, both using Babcock's coude spectroscopic method; Ermanno Borra and me with the UWO Balmer-line Zeeman analyzer; the Magnetic Mafia of the Special Astrophysical Observatory, who started a major observing programme under the leadership of Yurij Glagolevskij in the late 1970's using the spectrographs and Balmer-line Zeeman analyzer of the 6 m telescope; Gautier Mathys, using the Cassegrain spectrograph and coude echelle of the European Southern Observatory 3.6 m; and Jean-Francois Donati, Gregg Wade, and me with the Musicos spectropolarimeter at Pic-du-Midi.

Measurements of stellar magnetism have steadily advanced in number and in quality. We now know fairly accurately the longitudinal field variation for about 80 stars, and the variation of the mean field modulus (or surface field) for about 25. The precision of the best longitudinal and surface field measurements has reached 20 or 30 G, and even smaller errors should soon be available. Mathys has showed that other field moments, such as the crossover field and the mean quadratic field, can be detected in appropriate spectra, and has published a number of variation curves of these moments. The variations in broad-band linear polarization produced by the transverse Zeeman effect in spectral lines has been detected and measured in a number of stars by Jean-Louis Leroy at Pic-du-Midi, and linear spectropolarimetry data are now available from the Musicos instrument.

• Closely related to the improving field measurements has been work aimed at modelling, and more recently, mapping the distributions of magnetic flux and of chemical abundances over the surfaces of the magnetic Ap stars. The pioneer in this field was Armin Deutsch, who in the 1950's tried to use available longitudinal magnetic field, radial velocity, and equivalent width measurements of CS Vir to define Laplace expansions describing abundance and field distributions over the surface of the star, by relating the Laplace expansion coefficients to Fourier fits to the observational data. This pioneering work has been followed up starting in the 1970's by a number of people, including Vera Khokhlova, Tanya Ryabchikova, and Nicolai Piskunov of the Institute of Astronomy in Moscow (eventually together with several colleagues in mathematics at Moscow State University); Bill Wehlau and John Rice from Canada; Claude Megessier in Paris; and me. Gregg Wade, as well as Martin Stift and Stefano Bagnulo in Vienna, are increasingly active in this field as well.

Mapping of surface abundance distributions (for low-field stars, where the direct influence of the magnetic field can be neglected) is becoming increasingly secure and detailed. The magnetic field has typically been modelled rather than mapped, using, for example, a low order multipole expansion; but this is beginning to change. Techniques are being developed for carrying out simultaneous mapping of abundances and field geometry. This is an area of great current interest.

• The search for and study of magnetic white dwarfs has been a major ongoing area of research. The group at the University of Arizona, started by Roger Angel and now led by Gary Schmidt with Jim Liebert, continues to be very active. Other important groups working in this field include the team at the Special Astrophysical Observatory under Sergei Fabrika; a group in Britain; a group at the Australian National Observatory; and several German astronomers. We now know about 50 isolated magnetic white dwarfs. The detected fields range from a few tens of kG to about 10^8 G. For the brightest white dwarfs, field measurements accurate to a few kG are possible. About half of the magnetic white dwarfs are known to vary due to rotation; a considerable number apparently either do not rotate with periods of less than decades, or have aligned rotation and magnetic axes. The spectra of these stars are becoming well understood as atomic physics groups work out the expected magnetic splitting of atoms of H, He, etc. in the enormous fields observed, and the results are applied to observed stars. Modelling of the field structure so far has assumed simple field structures such as multipole expansions.

4. Major questions for the next century

You will agree that the information we have obtained about stellar magnetism during the past century, and the progress we have made in interpreting it, are really impressive. Nevertheless, there are a number of basic questions which still remain to be answered; in fact, it seems that some of the most fundamental questions are the very ones on which we have so far made the least progress. This is discouraging, in one way, after so much work; but it also means that young astronomers coming into our fields still have really important problems to address. Here are some of the problems that still need to be solved.

• A group of fundamental questions that have not really received a satisfactory answer concern the origin of stellar magnetic fields. We find evidence for fields in many regions of the Galaxy, and in dense clouds in particular; fields are now being detected in T Tau stars, the immediate progenitors of lower main sequence stars, and in Herbig Ae stars, the forerunners of A and B stars. We suspect that the fields of main sequence A and B stars are fossil remnants of the galactic field, though we do not know clearly how this field is conserved during the deeply convective pre-main sequence phases. We do not have any clear idea of how magnetism evolves from the galactic field to the fields of solar-type stars. It is not yet clear what role fossil magnetism plays in the formation of lower main sequence stars, nor what, if any, kind of dynamo activity occurs during evolution to the middle main sequence. We do not yet understand at all clearly why most middle main sequence stars do not seem to have magnetic fields. This subject needs much further observational work, searching for weaker fields to try to see more clearly where the fields occur and where they are really absent. There is also a great need for theoretical work to follow, at least roughly, the evolution of flux through the stages of cloud collapse and star formation.

• Similarly, we do not yet understand satisfactorily the further evolution of stellar magnetism after the main sequence. We have no evidence at present that strongly suggests *any* successors to magnetism in solar-type stars. For the middle main sequence, the existence of apparently fossil fields in a small fraction of all white dwarfs suggests that the magnetic Ap's evolve to become the magnetic white dwarfs. Whether this is correct, and if so how the field evolves during the deeply convective giant phase are still quite unclear. A further conundrum is that apparently most or all neutron stars are formed with huge fields. We do not yet know why this is so.
Again, both theoretical and observational progress is required. Detection of a weak field in a few giants could help to clarify the evolution through this phase. Modelling of field evolution during the giant stage is also very important.

• The internal physical state of magnetic Ap stars is still not clearly established. The basic run of variables such as p and T is clear, but uncertainty exists concerning the form and importance of rotation-induced (Eddington-Sweet) meridional circulation, the precise extent of convective layers, the extent of mixing due to "turbulence", and the degree to which the field enforces rigid-body rotation. The importance of diffusion is clear, but its effects are still not well understood, as they depend on the results of competition with all the mixing processes mentioned above, and require massive amounts of rather accurate atomic data for good calculation of radiative accelerations.
The upper boundary of the star is also an important parameter in diffusion calculations: is the atmosphere closed, is there selective radiative loss of atoms from the atmosphere, or is there a (more or less) well-mixed weak wind that includes H and He? Or is there (sometimes) accretion? How important is the magnetic field in modulating any mass loss (or gains), and what other effects does it have on the transport of specific elements into and out of the visible atmosphere? This is a subject which should greatly benefit from mapping of chemical and magnetic distributions on the stellar surface, and from any new techniques discovered that allow us to observe the postulated winds directly. It is also another area in great need of more theoretical studies; Babel's pioneering work on wind

structure needs to be continued.
As a consequence of the large areas of uncertainty mentioned above, there is still no single star for which we are able to predict either the general abundance table or the distributions of specific elements over the stellar surface correctly. There is still a lot of work for good theorists in this field!

• The interpretation of the roAp pulsations is another area in which much important work remains to be done. We have not yet securely identified the pulsation mechanism in these stars, nor the mode-selection mechanisms which excite only a few of the many possible vibrations. In fact, even the identification of specific pulsation modes in the observed oscillations is generally quite difficult and uncertain. Furthermore, the study of the effects of these oscillations on spectral lines, which should yield further valuable insight, has only begun. The amount of information that will be available about the internal structure of a number of magnetic Ap stars when these problems are solved is so great that this field certainly deserves intensified observational and theoretical studies.

• Another topic that I feel is of continuing interest is the observational study of populations distributions of various types of magnetic stars, their membership and frequency in clusters, their frequency and distribution among the local field stars, and their occurrence throughout the galaxy. Such studies have real potential for helping to understand the evolution of the fields and associated characteristics such as slow rotation and chemical peculiarity; increased telescope apertures and improved spectrograph efficiencies mean that we can expand previous samples by a considerable factor and perhaps resolve the inconsistencies and conflicting conclusions that have resulted from previous population studies.

• The nature of the dynamo that produces the solar field is still far from clear, and *a fortiori* so is the nature of the dynamo operating in other solar-type stars. This is very difficult theoretical problem, but it underlies much that we would like to understand about the Sun and similar stars. In the same context, the action of the solar field in heating the magnetically active regions of the chromosphere and corona, and the mechanisms involved in the formation of such large and obvious structures as prominences, still require considerable theoretical (and probably observational) work.

• Finally, the spectra of magnetic white dwarfs appear to be understood reasonably well for fields of less than a few times 10^7 G in H-rich atmospheres, and even in He-rich ones, but the observed spectra above 10^8 G continue to defy detailed modelling. There is room for further theoretical work here on both on the relevant atomic physics and on the formation of spectra in these huge fields, as well as further observational work of both intensity and (particularly) polarization spectra.

I think it is abundantly clear that we still have many important and very interesting problems on which to work, and which we can propose to students and young researchers. I am quite confident that our fields will remain exciting and challenging well into the next century.