PART I
The Department of Celestial Magnetism

by VIRGINIA TRIMBLE

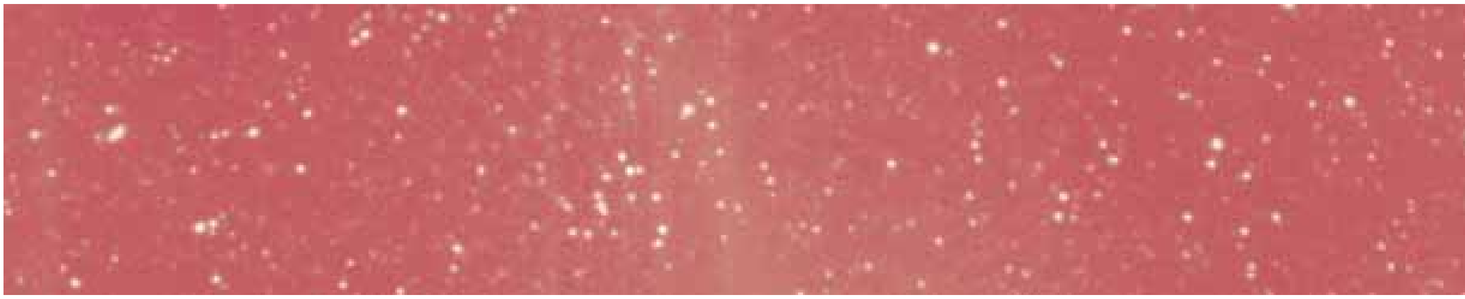
"The larger our ignorance, the stronger the magnetic field."

—Lodewijk Woltjer,
Nordwijk Symposium, 1966

Astronomical Society of the Pacific

Fritz Zwicky, who was right about a lot of things, used to claim that producing astrophysical magnetic fields from scratch was so difficult that the solution must lie in a phrase accidentally omitted from the printed version of Genesis 1:14, "Dixitque Deus: Fiat lux, campusque magneticus."* Many of us also suspect that, while the Creator proclaimed the light to be good, if He had seen the magnetic fields, he would have joined us in regarding them as a tiresome and unnecessary complication.

**If you are looking for the Hebrew original of what God really said, ask any Israeli physicist; they still speak it. If what you had in mind was English, "And God said: Let there be light . . . . and magnetic fields" is a reasonable approximation. Zwicky was widely reputed to speak seven languages, all badly. I am not sure whether this was meant to include Latin.*



Why should the celestial magnetic landscape look untidy? Electromagnetism is, after all, a solved problem. Maxwell's equations provide a complete, special-relativistically correct description of charges, currents, fields, and their interactions, apart, perhaps, from the missing corner of the tablet that must have contained the rest of the equation that begins $\nabla \cdot B =$, so that we cannot be sure whether the right-hand side is zero or merely very small. Quantum electrodynamics, as gradually assembled by Hans Bethe, Richard Feynman, Julian Schwinger, Shinichiro Tomonaga, Freeman Dyson, and, probably, others, takes care of the quantum mechanical side of things. Thus, once you decide which calculation to do, there is a single, correct way to do it. The astrophysical difficulty is that we are not quite sure which calculations to do.

Magnetic fields in astrophysical objects are supposed to be of three kinds. First, there are fossil, residual, or frozen-in fields. The idea is that, if you take a magnetic field and put it in a box with a plasma, it will probably still be there, flux conserved, later on, even if you have expanded, compressed, or stirred the contents of the box in between. Judicious stirring can even amplify the field sometimes. Magnetism in dead stars— white dwarfs and neutron stars—is generally described as being of this type, with flux conserved from when they were real stars, with nuclear reactions in progress.

Second, there are dynamo fields, continuously regenerated by electric currents of suitable geometry, drawing their energy from rotation, turbulence, or other mechanical sources, and requiring a small seed field to get started. The earth, the sun, and the Milky Way galaxy are believed by most to have dynamo fields. All three have suitable substances to carry the currents (the earth's fluid iron core; ionized gases in stars and interstellar medium) and a combination of rotational and turbulent energy to draw on.

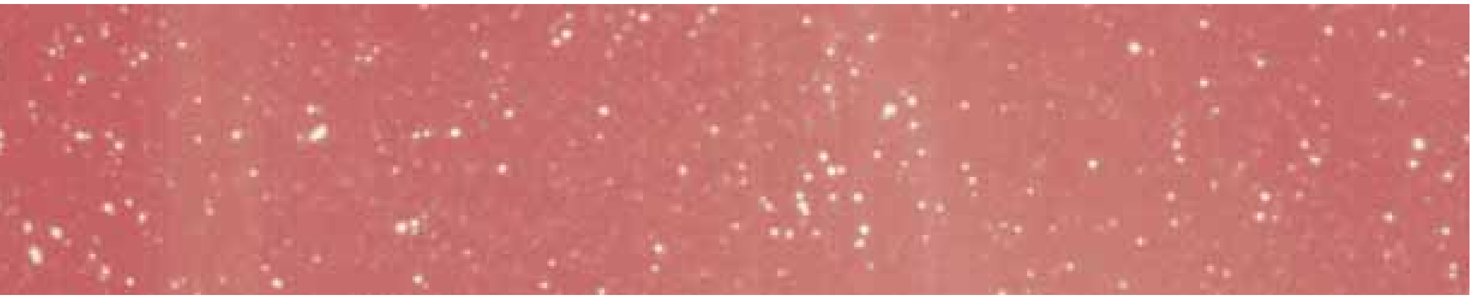
The really big question is, of course, how much (if any) of the preceding two paragraphs is true. Both mechanisms require some previously existing field and so in a sense just push the problem a bit further back in time, to the third class of astrophysical field, the primordial. And in none of the cases can we specify the initial conditions well enough to calculate anything with the sort of rigor that you chaps over in physics generally expect. I will defer further discussion of origins until after page 51.

Meanwhile, there are some simpler questions to which partial answers exist: Which astronomical objects have magnetic fields? (All of them, it seems.) What are their geometries and intensities? What other phenomena are they responsible for, and how would the universe be different without them? And, of course, how do we know these things? Curiously, given their ubiquity, astrophysical magnetic fields are not often dynamically important, and the answer to "how different" is frequently "not very." Our most important tools are the Zeeman effect and Faraday rotation of linearly polarized light. Our units are relentlessly cgs.

FROM EARTH TO MOON IN A FRACTION OF A GAUSS

The earth is the only astronomical object that has been known to have a magnetic field for even as long as a century. Credit for the discovery belongs to the Chinese, the Greeks, or the Asians Minor, depending on how much faith you put in the "south pointing carriage" of the emperor Huan Tin, the shepherd Magnus, or the Hills of Magnesia. The approximate dipole shape and strength first revealed themselves to William Gilbert in about 1600 and secular changes to Edmund Halley in 1692. The former has a unit named for him and the latter a comet. The comet is about 10 km long; anyone who can explain the size of a gilbert is entitled to a glass of wine at the next APS meeting we both attend.

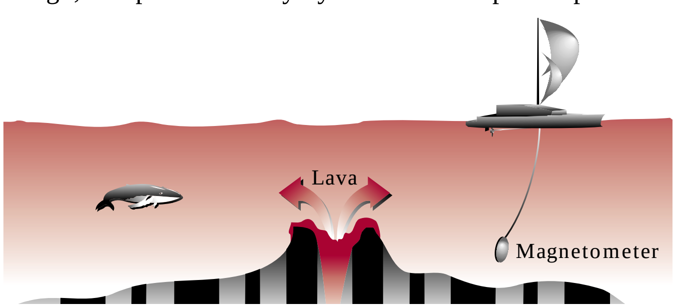
The present average strength of the earth's surface field is a bit less than half a gauss, varying systematically with latitude and more chaotically with types of nearby rocks and so forth. The north and south magnetic poles coincide with the geographic ones only on average, and the westward drift of field pattern discovered



by Halley was part of the averaging process. He was not, and could not have been, aware of a much more spectacular kind of change. The earth's field reverses (flips upside down) every half million years or so (174 changes in the last 100 million years, but the epochs are not all of equal length). In more elegant words, the earth's field is an over-stable, self-excited dynamo, with a quasi-period of about 5×10^5 years.

What is our field good for? Sociological items come first to mind: the importance of magnetic compasses to 13th–19th century navigation and, more recently, to the location of boy scouts by girl scouts, and conversely.

Only the twisted mind of a frequent teacher of introductory geophysics would think next of the importance of evidence from fossil magnetic fields in persuading much of the geophysics community of the reality of sea-floor spreading and continental drift during the period 1955–1965. The key observation is that undersea rift valleys, like the East Pacific Rise and the mid-Atlantic Ridge, are paralleled by symmetric stripes of positive and negative field anomalies, about a milligauss in strength and 10's to 100's of km wide. The interpretation is that the rifts are spreading centers and that magnetic domains in new, fluid basalt continuously solidify aligned with the instantaneous terrestrial field, parallel or anti-parallel to the present one, only to be dragged relentlessly away from their rift of origin. The strip widths plus calibration of the times of field reversal (based on radioactive dating of continental lava flows) tell you that the oceans are opening and closing at a few centimeters per year. Fossil magnetic fields in continental igneous rocks more than a few tens of millions of years old also say that both the latitudes and the orientations of the continents have changed with time.

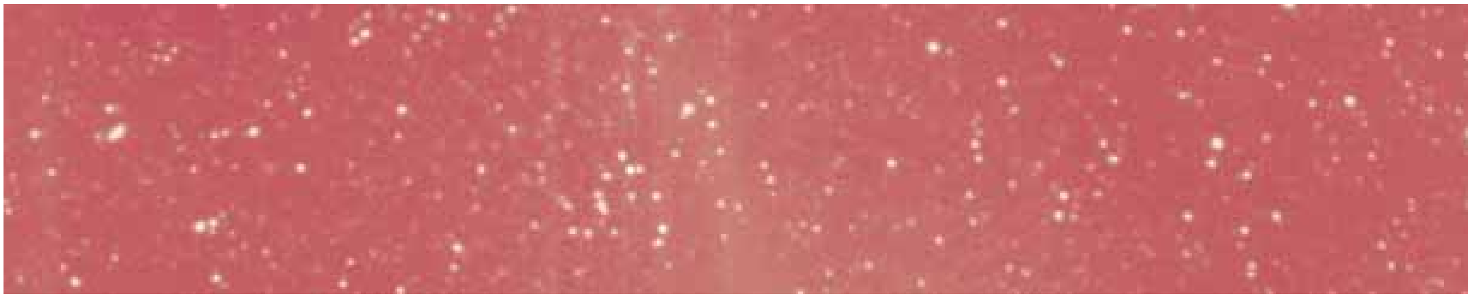


Seafloor spreading (symbolic view). The shaded pattern shown is that of residual magnetic fields, after the local average has been subtracted. Lighter stripes have residual field parallel to the earth's present dipole, including the central stripe of material currently being solidified from fresh lava. Darker stripes have reversed residual polarity. The figure is probably about 100–200 km across, representing 3–6 million years of motion. The whale, magnetometer, and vessel belonging to Scripps Institute of Oceanography are, therefore, not to scale. Arrows show the direction of plate motion. Modern oceanographic vessels are generally not sail powered.

The terrestrial magnetic field extends (with strength $\propto 1/r^3$) well above the earth's surface, where it is responsible for trapping energetic particles in the Van Allen belts and for standing off the solar wind in a bow shock out at about 10 earth radii, with a tail trailing out behind us. Energetic particles that do reach the earth's surface are a major source of mutations, suggesting our field has biological importance. Efforts to associate periods of rapid extinction with episodes of field reversal, when field strength goes briefly through zero, remain fairly indeterminate.

Keeping up the earth's field with dynamo processes presents something of an energy problem. This sounds screwy. The rotational kinetic energy is more than 10^{36} ergs. The energy dissipated per field reversal cycle ($B^2/8\pi \times$ volume of earth) is only 10^{18} ergs for a one gauss field. But, it seems, only the convective energy flux is available for use, and the internal toroidal field is a hundred times or more stronger than the surface dipole one. Thus a conversion efficiency of about 10 percent is required—not impossible, but surprising.

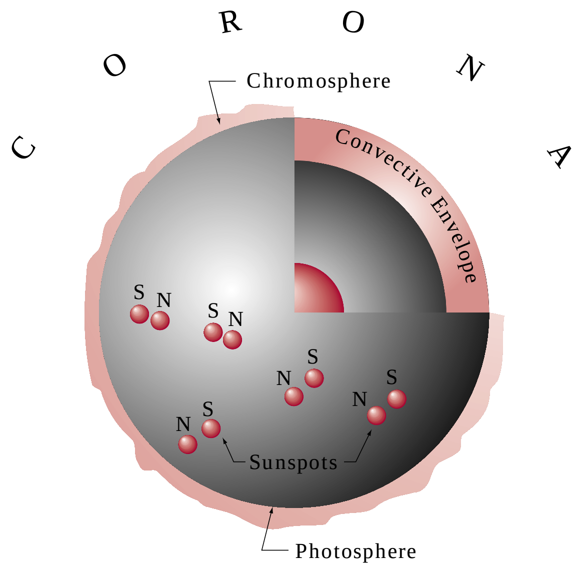
The moon, in contrast to the earth, is magnetically dead, with little or no magnetosphere or dipole field. The rocks returned by the Apollo astronauts and their in situ magnetometer measurements, however, both displayed local fossil fields up to a few milligauss (comparable with typical frozen-in anomalies in terrestrial rocks).



THE SUN AND SOLAR SYSTEM

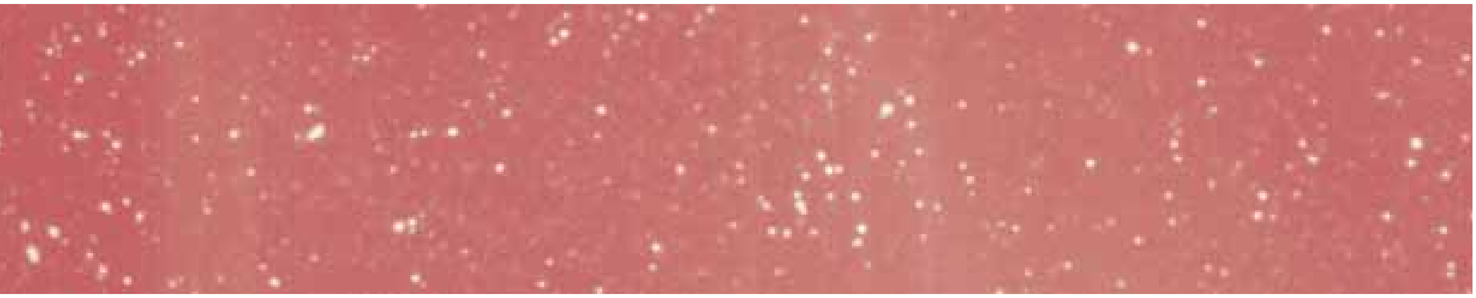
Our Friend The Sun became the second astronomical object with a known magnetic field sometime between 1892 (when John Young observed the doubling of some absorption lines in the spectra of sunspots) and 1908 (when George Ellery Hale measured opposite circular polarizations for the two components coming from spots at the center of the solar disk). This is, of course, the classic Zeeman pattern for field lines parallel to your line of sight, that is, perpendicular to the surface of the sun.

George Ellery Hale discovered the magnetic field of the sun and many of its systematics. One goal at which he failed was that of photographing the corona at times other than during total solar eclipse. The necessary device was developed by others after Hale's death and is comparably clever to his device for obtaining solar magnetograms (shown here).



Layers of the sun responsible for the various tracers of solar magnetic field and activity (partial cutaway). Energy is generated in the small, shaded core and carried outward by radiation. The outer layer is convective, and fluid motions here are somehow involved in dynamo field generation. The photosphere is the layer you see, complete with sunspots, with their polarities shown for some representative 11 year half-cycle. The chromosphere is only a few thousand miles thick and emits line radiation responsible for K line reversals, etc. The corona extends out to many solar radii (more at cycle maximum), blending into the solar wind. At a temperature of about 10^6 K it emits X-rays and bremsstrahlung and synchrotron radio waves (more during flares).

The 11 year sunspot cycle had been recognized about 75 years before, and Hale went on to demonstrate that, during a given cycle, all spot pairs in the northern (geographic) hemisphere have their right-hand spots of one polarity and their left-hand spots of the opposite polarity, with things backwards in the southern hemisphere. And everything flips around the other way (including the sign of the 0.3 gauss overall dipole field) in the next cycle. Thus the real period is 22 not 11 years. Fields in the spots and surrounding active regions range from hundreds to a few thousand gauss.



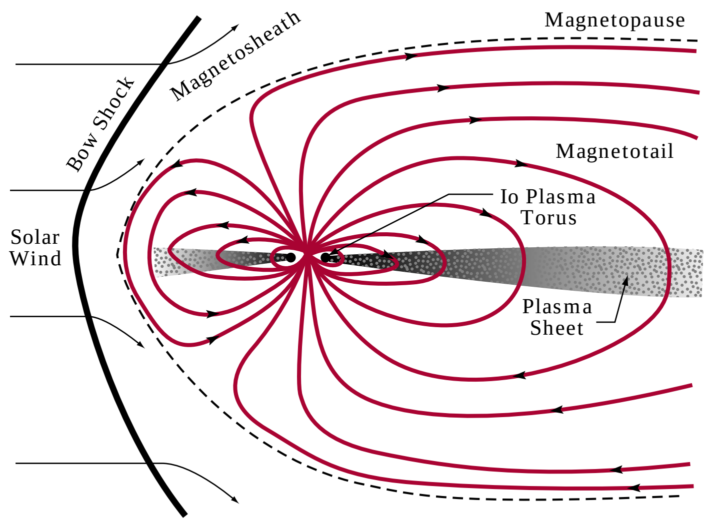
The solar activity cycle, with spots, flares, enhanced corona, and bursts of wind and energetic particles all coming and going, is the most obvious manifestation of the sun's field. The variable ultraviolet, X-ray, and particle fluxes show up on earth as changes in the ionosphere (hence in propagation of radio and radar signals), in carbon-14 production, and in the ozone layer. Not all the changes go the way you might think. The particle burst from a major solar flare can knock out over-the-horizon radar for days (and has, with occasional near-serious consequences); but you get the most C^{14} made during cycle minimum, when the solar wind is weak and allows more galactic cosmic rays to come in from outside. Nobody quite knows how far you have to go to reach the edge of the heliosphere, where the wind finally comes to terms with interstellar gas and fields, but it is anyhow well outside the orbit of Pluto, and the Pioneer and Voyager space craft have not yet got there.

Large numbers of observers and theorists earn their precarious livings by reading each others' preprints about properties and models of various aspects of the solar activity cycle. Most models derive at least remotely from ideas put forward in the 1950s by Horace W. Babcock and Robert Leighton, in which the overall dipole is stretched and amplified by solar differential rotation and convection until bits start popping out at mid-latitude. More work is needed.

A less obvious consequence of the solar field is gradual slowing of the sun's rotation, of which more later under "nearly normal stars."

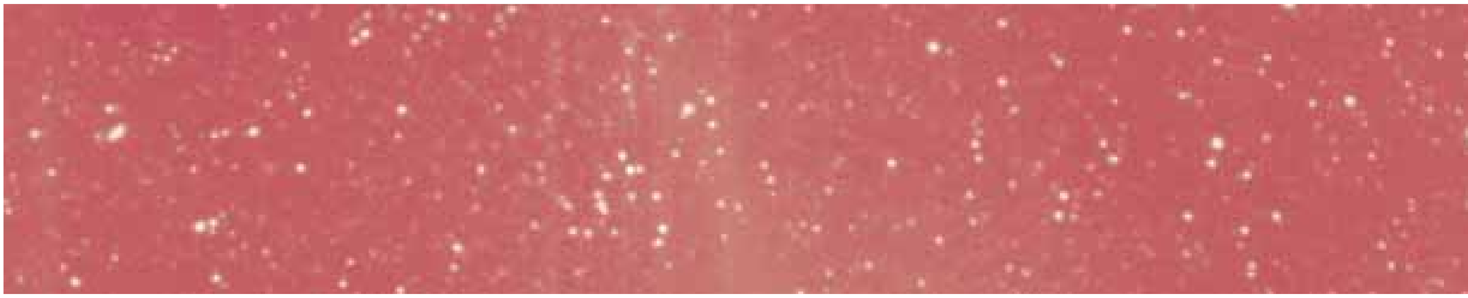
The other terrestrial planets (Mercury, Venus, Mars) have dipole fields and magnetospheres at most 1 percent that of the earth. My explanation in introductory classes is that Mercury and Mars lack fluid cores, while Venus is a slow rotator. All are true, though the experts say things are really rather more complicated. The most clearly measured of the three dipoles, Mercury at 330 nT, is apparently a frozen-in field, left from when the planet had some partly molten, metallic materials, threaded by the field of a younger, more active sun. My favorite overestimate was a 1962 suggestion of a 5000 gauss field for Venus, based on appparent decline in geomagnetic activity when Venus was closest!

The Jovian planets (Jupiter, Saturn, Uranus, Neptune) all have measurable fields and magnetospheres with radii 10–100 times those of the parent planets. The Jovian field is strongest, from 3–14 gauss. The others are all about 0.9 G at their magnetic poles and weaker elsewhere. No two of the planets have the same angles between field axis and rotation axis (or between rotation axis and orbit plane), and none is much like the earth. Thus you will need a different sort of compass for each one you decide to visit.



The magnetosphere of Jupiter showing the shock of encounter with the solar wind, the trailing tail, and the radio-emitting plasma connected with the moon Io. (Courtesy of Fran Bagenal, University of Colorado, Boulder)

The great strength of the Jovian field means that the dinosaurs there could have seen aurorae much more spectacular than those of earth up until they were all killed by the impact of Comet Shoemaker-Levy 9. The motion of Jupiter's innermost large moon, Io, through the magnetosphere drives some impressive radio emission, though the animals that could sense it became extinct long ago, owing to the enormous ergonometric burden of carrying microwave antennae on their heads. The giant planets are all largely made of rapidly rotating plasmas, and field models are dynamos of various sorts.



NEARLY NORMAL STARS

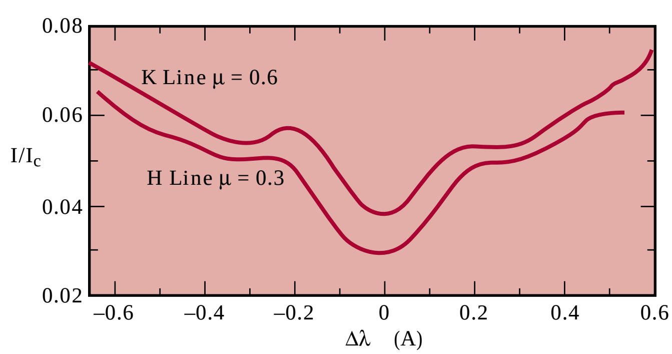
Searches for Zeeman splitting and polarization in stellar spectra began just a few years after Hale's solar triumph, but the first winner was Horace Babcock in 1946 (same guy, and not to be confused with his father H. D. Babcock, who was, however, his collaborator on many papers dealing with solar magnetism). The star was 78 Virginis, probably not one you have often wished upon. Young Babcock made several wise choices—a big telescope (the Mt. Wilson 100-inch), an analyzer with mica quarter-wave plate and calcite crystal that minimized instrumental loss of light and was much like a device Zeeman himself had used, and concentration on spectral lines produced by atoms of iron, chromium, and cobalt, not the more obvious, stronger lines of hydrogen. The disk-averaged field in 78 Vir implied by the wavelength separation of right- and left-circularly polarized lines was about 1500 G.

The Carnegie Institution of Washington, Pasadena, California

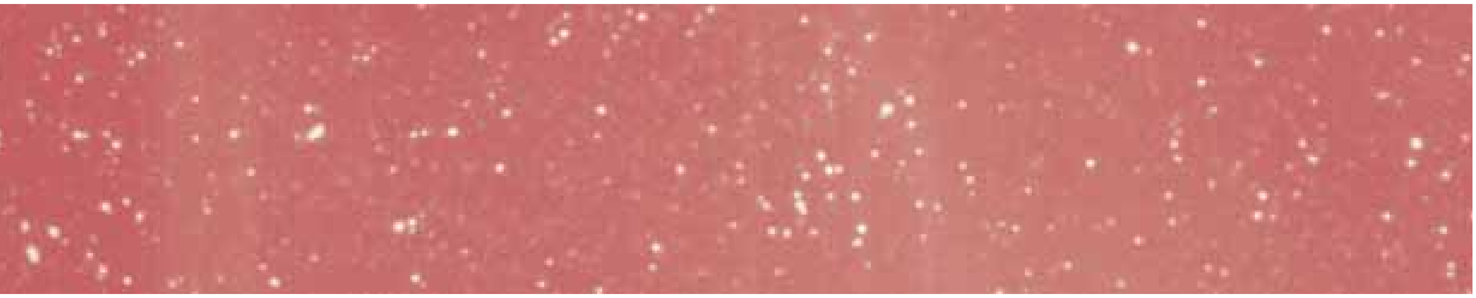
Horace W. Babcock, discoverer of stellar magnetic fields and modeller of the solar one. Believe it or not, his Ph.D. dissertation was on the rotation of the Andromeda galaxy and counts as one of the very early discoveries of dark matter.

Babcock was also lucky. He had chosen to look at stars with surface temperatures of 10,000–20,000 K (types A and B), most of which are rapidly rotating, on the grounds that they ought to have stronger dynamo fields (Larmor had already attributed the solar field to dynamo-like action back in 1919). And he picked out a subset with narrow lines, because otherwise Zeeman broadening would be obscured by Doppler broadening, on the assumption that they were seen pole-on. But his sample included a few stars known to have exceedingly peculiar spectra, with greatly enhanced lines of europium and other lanthanides. These stars are actually slow rotators with periods of many days (seen in the regular variability of their brightnesses, field configurations, and spectral line profiles), with regions of strong field and weird composition studded across their surfaces in long-lived, spot-like patterns. Local field strengths extend up to 50 kG, and many of the stars have their magnetic axes nearly perpendicular to their rotation axes. This "oblique rotator" geometry will appear again when we get to pulsars. These peculiar A (Ap) stars are still the only "normal" (hydrogen-burning) ones with magnetic fields strong enough for Zeeman broadening to be seen from earth.

Nevertheless, the study of stellar magnetism and related activity is a major astronomical enterprise, because we can look for analogs of solar field indicators. Among these are flares, radio and X-ray emission from coronae (advertized as being heated by Alfven—magnetohydrodynamic—waves), and variability in brightness caused by groups of dark spots carried along with the rotating stellar photospheres. The most useful indicator of all has been the peak of emission that pokes up at the bottoms of strong absorption lines (H-beta, the

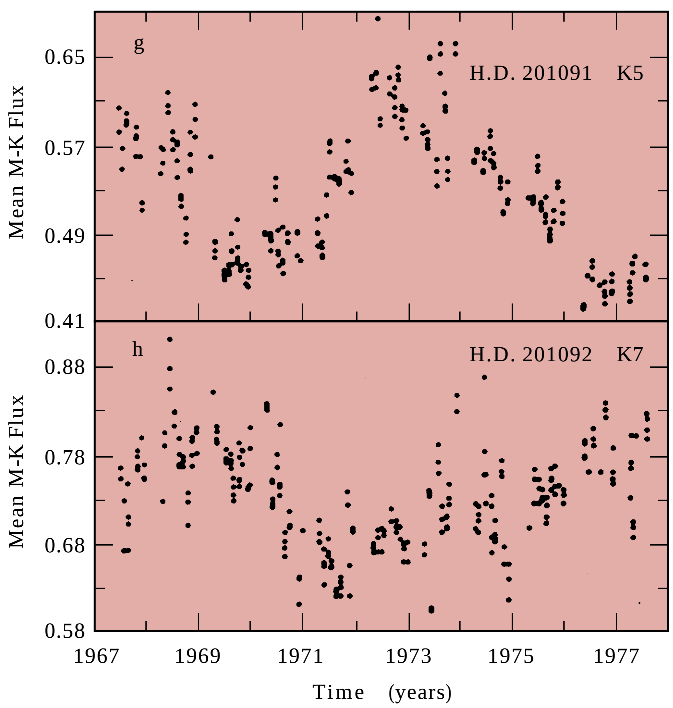


Emission line components in the solar lines of Ca II (calcium H and K). The photospheric absorption extends the entire ±0.6Å width of the figure and beyond. The emission pokes up from it between +0.2 and -0.2Å from the line center. And there is a final absorption dimple at the center where even the chromosphere is optically thick. [Adapted from article by J. B. Zirker in The Structure of the Quiet Photosphere and Low Chromosphere *(Bilderberg Conference, 1968), Reidel.]*



H and K lines of ionized calcium), discretely in the sun, and blatantly in some other stars. These so-called line reversals are photons coming from (magnetically?) heated chromospheres. Their intensity in the sun is greatest where there are most spot groups, flares, prominances, and other heating sources.

Thus, way back in 1913, Karl Schwarzschild (of the black hole solution) had asked rhetorically whether one might not be able to find cyclic variations in calcium K-line reversal intensities, thereby demonstrating the existence of solar type cycles in other stars. The answer is yes. Olin Wilson started looking hard in the early 1960s



Changes with time in the H and K emission in spectra of two stars somewhat cooler than the sun. For HD 201091 evidence for a period near seven years is fairly clear. HD 201092 is clearly variable but less obviously periodic. Other stars show an essentially constant, low level of emission for decades. More recent data are not cleaner (though some now extend over longer time periods) because the short term fluctuations ar real, not instrumental errors. Reprinted with permission from the Astrophysical Journal.

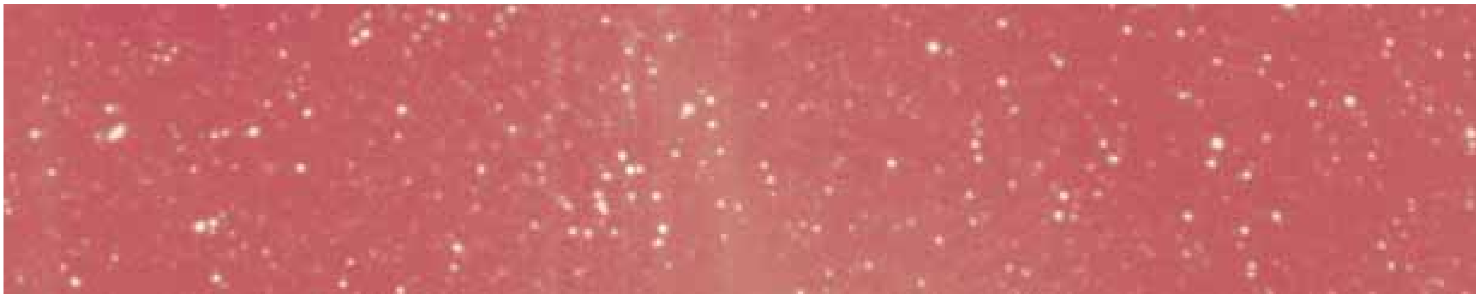
and, upon retirement, handed over the project to Sallie Baliunas, who has added many measured cycle periods, most between 5 and 15 years (partly an observational selection effect) to Wilson's handful. Curiously, the Mt. Wilson 100-inch telescope is still among the facilities she uses.

Stellar activity, according to these various and well-correlated indicators, is best predicted by Rossby number. Eh? Translation—you get lots of activity (driven, we presume, by strong dynamo flelds) when the star is a rapid rotator having a deep convective envelope. Convection sets in at a surface temperature a bit below 10,000 K, reaches down 30 percent of the radius in a 5700 K sun, and takes in the whole star below 4000 K. And, indeed, the most spectacular flares come from faint, cool stars. Rapid rotation is a gift of stellar youth and dies away in 10^{7-9} years, except in close pairs of stars, where rotation and orbit are synchronized, so that a rotation period of a few days lasts forever, instead of slowing to a month or more as in the sun.

Where does the rotation go? It is carried off by magnetized winds that co-rotate out to large distances and then dump angular momentum where they interface with interstellar gas. Thus our sun was almost certainly a rapid rotator 4.5 billion years ago when it first formed, as are solar-mass stars in young clusters today.

Does any of this matter to the price of beans? Maybe. A more active, young sun implies more ultraviolet radiation, X-rays, and high energy particles reaching the earth to affect its atmosphere, hydrosphere, and biosphere. There may even have been nuclear reactions among flare particles, making lithium and a few other rare nuclides.

But the most important possession of the rapidly rotating proto-sun was its protoplanetary disk. Indeed, through the 1920s and 1930s, mainstream opinion held that our planetary system must have resulted from a close encounter between the sun and another star, because there was no way to achieve the present distribution of angular momentum between the sun and planets in a closed box system. True enough; it's just that the box is open at the opposite end from what



Chamberlain and Moulton had in mind, and angular momentum gets out rather than in.

Stellar encounters close enough to drag out material for planets will happen about once per galaxy in the age of the universe (even if you could be sure of the stuff condensing afterward). Protoplanetary disks, in constrast, are common around newly-forming stars. They can be studied because gas and molecular gas in them emit continuous and band radiation in infrared and millimeter regimes. Thus the rapid rotation of young, cool stars and their consequent dynamo magnetic fields are intimately connected with the existence of the earth and other potentially habitable planets orbiting other stars.

You will probably have noticed that the strong, spotty fields of the Ap stars are not part of this rotation + convection pattern—their atmospheres are radiative and they are slow rotators. Thus the origins of their fields are even less well understood than those of solar-type poloidal + toroidal fields, powered by alpha-omega dynamos. Alpha is the convective part and omega the rotation, and I have no idea whether the person who coined the name had any religious associations in mind!

THE REALLY BIG FIELDS—NEUTRON STARS AND PULSARS

European Southern Observatory

Lodewijk Woltjer. Later director general of the European Southern Observatory, Woltjer for some years focussed on force-free magnetic fields in galaxies after completing a thesis on the Crab Nebula (another place where magnetic fields are important). He was among the pre-discovery predictors of neutron star fields.

Although white dwarfs entered the astronomical inventory early in this century and neutron stars not until 1968, the neutron stars had strong fields first, both predicted and measured (remarkably, in that order). Two rather similar, but apparently independent, predictions date from 1964 and 1967. In the former, Lodewij Woltjer wrote: "If a star contracts in a spherically symmetrical way and if flux is conserved [and] if neutron star densities are reached the field intensity would increase by a factor of 10^{10}, and thus stellar fields of up to 10^{14}–10^{16} G could be reached. . . .one may well speculate that such a theory could have a direct bearing on the problem of the origin and acceleration of the relativistic electrons in the Crab Nebula."

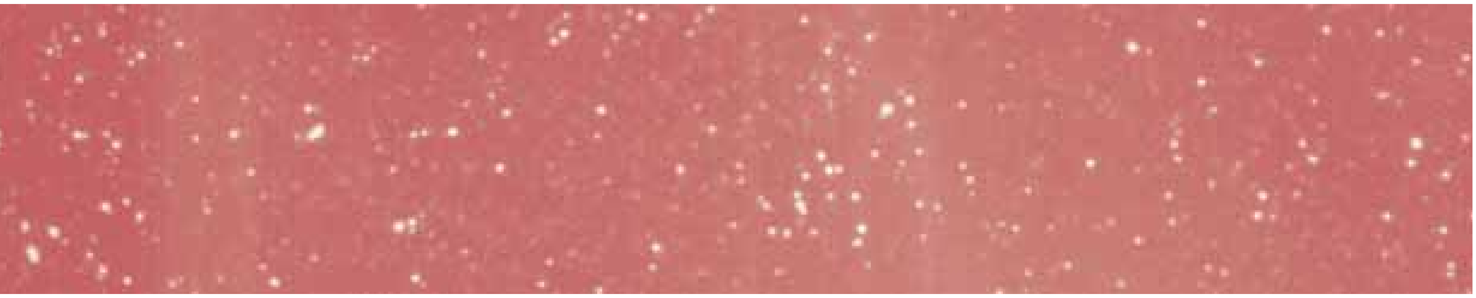
And Franco Pacini mused in 1967:

> The problem therefore arises of finding out whether the energy stored in the neutron star plays an important part in connection with the activity observed in some supernova remnants such as the Crab Nebula. The vibrations of the neutron star, however, do not last long enough for our purpose. . . . It seems more rewarding therefore to look for some mechanisms by which the neutron star can release either its magnetic or its rotational energy or both.

To which we can only say: Yes, one may and it does. Pacini, incidentally, continued by giving the equation for radiation by a rotating magnetic dipole that we now all use to calculate pulsar field strengths and ages, though pulsars had not yet been discovered.

The March 1968 announcement of pulsars by S. - Jocelyn Bell, Anthony Hewish, and others did not immediately pin things down, since wrong models outnumbered right ones (rotating oblique magnetised neutron stars) for the first few months.* Convergence came with a measurement of the rate of slowing down of the pulsar in the Crab Nebula, remnant of the 1054 supernova recorded by Chinese astronomers. Given the period, its derivative, and the relevant volumes of Landau and Lifshits, anyone could calculate the rate at which energy was being lost (yes, it was enough to power the surrounding nebula) and the dipole magnetic field needed to radiate that much energy. The answer is roughly 10^{12} G, a million or so times as strong as the strongest laboratory fields, but still small compared to what the stars could support without being distorted by magnetic pressure.

**This is not quite like always finding things in the last place you look, but there are similarities.*



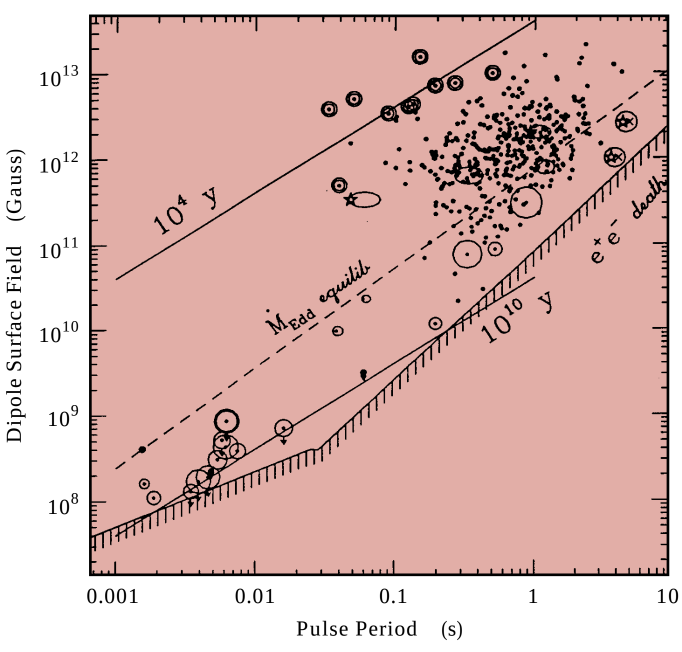
Nobody really quite knows how pulsars convert 10^{28} to 10^{38} erg/sec from dipole radiation at 0.2–600 Hz to the much higher frequencies and particle fluxes that we see, and, in accordance with Ehrenfest's remark about the difficulty of explaining things you don't understand, I won't try. At least one other major puzzle remains in the realm of neutron star magnetism, though all sorts of things have been measured in the decades since 1968.

A relatively narrow range of field strengths, $10^{12\pm1}$ G, takes care of (a) all pulsars with spin-down ages of 10^7 years or less, (b) the X-ray emitting neutron stars whose energy source is material from a massive companion star channelled down on to their surfaces by their fields, and (c) the subset of X-ray neutron stars whose spectra show cyclotron resonance features at energies of 20–70 keV. Within this class, field strength is not strongly correlated with rotation period, age, location in the Milky Way, or anything else you can think of. All single pulsars of this type have rotation periods between 0.033 and 5 seconds and are slowing down. The binary ones have periods of 2–1500 seconds and are as likely to be getting faster as slower. Thus we come to the other major mystery: just how do the objects described in this paragraph evolve to the ones in the next paragraph?

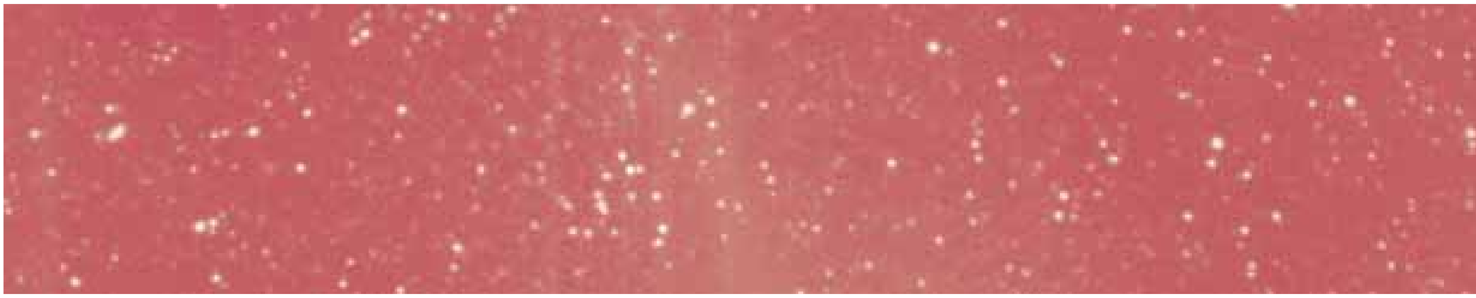
A second class of pulsars is characterized by (a) spin-down ages of $10^{8–10}$ years, (b) rotation periods of 1.55 to 100 msec, (c) dipole magnetic fields of $10^{8–10}$ G, and (d) frequent presence of companions (mostly white dwarfs or other neutron stars). They somehow go with a second class of X-ray binaries in which the neutron star is accreting from a low-mass, old companion and shows no evidence of either cyclotron features or magnetically-funneled accretion. The rapid rotation is blamed on spin-up by accreting gas during the X-ray phase (after which some, but not all, of the born-again neutron stars are liberated).

But where has most of the magnetic field gone? Did it just die away through enhanced Ohmic dissipation, removal by elves, or something? If so, why are there no field-age correlations among the younger objects? Has it merely been temporarily buried by the accreted gas (the "in" word is advected)? Perhaps, but we are not at all sure that all the single, millisecond pulsars have been through a binary phase.

Oh yes. Is it now definitely established that the fields are really the fossil, flux-conserving kind that Woltjer and Pacini predicted? Not at all. Theorists abound who prefer some sort of dynamo, Hall currents, or other *in situ* production mechanism. Many of the scenarios for field formation and destruction involve periods when most of the magnetic energy is in higher moments than dipoles. Such fields do not make for efficient pulsar



Locations of many pulsars, both normal (young) and reborn in a field-strength vs. period diagram. Period is directly measured. Field strength is calculated from P and dP/dt on the assumption of magnetic dipole radiation from a 1.5 $M_\odot$ 10 km radius neutron star ($B^2 = 10^{39}$ $P \times$ dP/dt, B in Gauss, P in seconds). Millisecond pulsars are in the lower left corner. Solid diagonal lines are the loci of pulsars whose slowing-down ages $t = P/2(dP/dt)$ are 10^4 and 10^{10} years. Neutron stars to the right of the hatched zone are not energetic enougn to make $e^{\pm}$ pairs and so do not radiate. Other symbols indicate membership in binary systems, presence of a supernova remnant, and so forth. [Courtesy E. S. Phinney and S. Kulkarni, Annual Reviews of Astronomy and Astrophysics 32*, 591 (1994).]*



emission and can be very hard to detect. Nor can I think of any way that the universe would be fundamentally different if neutron stars had no magnetic fields at all, or much stronger ones than they do.

THE MAGNETIC FIELDS OF WHITE DWARFS—A STELLAR AFTERTHOUGHT

No one seems to have estimated or searched for magnetic fields in white dwarfs (the remnants of burnt out stars of relatively low mass) until pulsars (the corresponding remnants of bigger stars) had been seen and crudely understood. Soon after, most of the people you would expect entered the prediction market (J. P. Ostriker at Princeton, V. I. Ginzburg in Moscow, Woltjer at Columbia), pointing out that fields of megagausses and more would result from the same sort of flux conservation that seemed to apply to neutron stars.

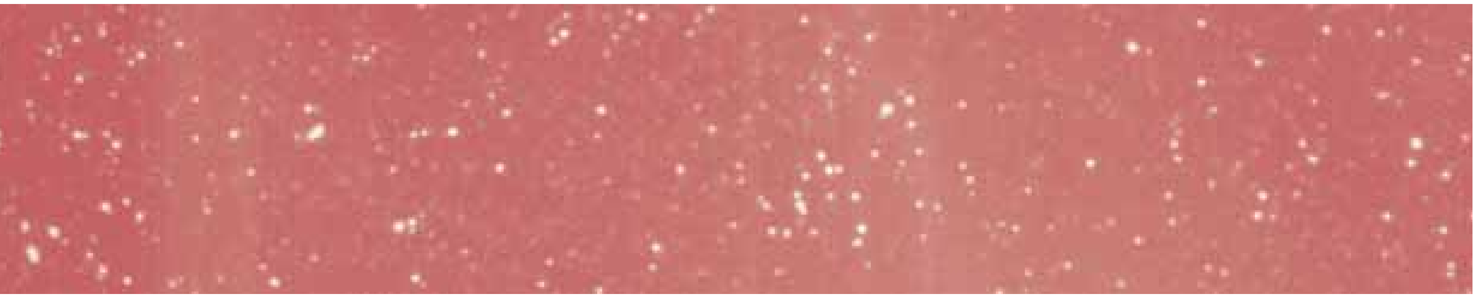
The secret to successful measurement was finding the right lamppost to look under. George Preston of the Hale Observatories thought of quadratic Zeeman shifts of hydrogen absorption lines in white dwarf spectra (the majority of which display nothing else; helium only is second commonest; and third comes no lines at all). He used wavelengths for 70-some stars, published in the preceding few years by Trimble (yes, that Trimble) and Greenstein (Jesse L. of Caltech) and arrived at an upper limit of less than 10^6 G for all of them. Unfortunately, he had neglected to consult the data gatherers—an act not totally unprecedented among interpreters. We had, in fact, thrown out the higher Balmer lines when they disagreed with the stronger, longer-wavelength ones, automatically eliminating the possibility of seeing any quadratic Zeeman effect. Rootling back into the raw data, I discovered what first looked like many fields at the few Megagauss level. It was actually an obscure, previously unimportant, wavelength-dependent curvature of lines on spectrograms exposed through the prime focus spectrograph of the 200-inch Palomar telescope. And we were back to (slightly looser) limits on white dwarf fields. This was not the right lamppost. It still isn't. The majority of white dwarfs have fields too weak for quadratic Zeeman shifts to be seen even today. As for the rest, stay tuned.

The winning strategy was circular polarization. A couple of upper limits appeared back-to-back with Preston's I970 Zeeman paper, and a detection the next year. The telescope used was not the 200-inch or even the 100-inch, but a 24-inch at Pine Mountain Observatory (wherever that is). The first observer was not any of the famous people at Lick, Palomar, or Kitt Peak, but James C. Kemp of Oregon State University, primarily a laboratory physicist. And the field he found was not a mere Megagauss but considerably more than 10^7 G. The star, however, was famous, called Minkowski's star for Rudolph, who took the first spectrogram of it in 1938, said he could make neither heads nor tails of its spectral features,and went back to supernovae and galaxies.

Strangely,* the star is now more often called Grw +70˚8247 (meaning the 8247th star in a zone of the sky 70˚ north of the celestial equator as recorded in a catalogue compiled at the Greenwich Observatory), and it has been followed by several dozens of white dwarfs (a few percent of the ones examined) with fields of 3 to 300 MG or more. At this field strength, all degeneracy of hydrogen energy levels disappears, and the components of the Balmer lines run, seemingly at will, all over the wavelength landscape. The features you see correspond to components whose wavelengths remain relatively constant over some reasonable range of Megagausses.

Megagauss-plus magnetism is commoner among binary than among single white dwarfs, turning up in 10 percent or more of them, vs. a few percent of the singles, but the fields are confined to a much narrower range of 20–50 MG. This is, of course, not understood. The fields are fossil ones by default—nobody has figured out how to make them in the degenerate dwarfs. Thus obviously one ought to look for some kind of correlation with the fields in the progenitors of binary vs. single white dwarfs. Well, we did anyhow agree a section or

**Perhaps not. This is, after all, the generation that prefers http://to Dear Rudolph.*



two back that close binary stars, by continuing to rotate rapidly as they age, keep up their activity longer and thus, perhaps, their magnetic fields. Now you pick a hypothesis!

Binary magnetic white dwarfs often have coronae that produce emission lines, X-rays, and ultraviolet photons. Do the single ones, at least those cool enough to have convective surfaces? Apparently not. Several of us thought it likely enough to apply for satellite time to look for the X-rays, and the negative results are now sufficiently numerous that further requests are unlikely to be approved! Look for Zdzislaw Musielak as first author on one set of papers, Trimble as last author on some others, and theorist Vladimir Zheleznyakov, who was Ginzburg's co-author on one of the early prediction papers and, I think, has still not quite given up.

The magnetic fields of white dwarfs, like those of neutron stars, do not seem to make any great difference in the grand scheme of things.

INTERMISSION

So far, we have encountered magnetic fields, both dynamo and fossil, in planets and stars. In no case is the magnetic energy content even as much as 1 percent of the gravitational potential energy, nuclear energy, or other reservoirs in the objects. Please tune in next quarter for a look at some cases where fields are dynamically important (star formation, bipolar outflows, quasar jets) and some others (like the spiral arms of galaxies) where again they are apparently just along for the ride.

FOR MORE DETAILS (though personally I think you have had about enough for one day)

F. Krause et al. Eds. **The Cosmic Dynamo** (IAU Symposium 157), Kluwer (1992).

F. Bagenal, "Giant Planet Magnetospheres" in Annual Reviews of Earth and Planetary Sciences **20**, 289 (1992).

D. J. Helfand and J.-H. Huang, Eds., **The Origin and Evolution of Neutron Stars** (IAU Symposium 125), Reidel (1987).

V. Trimble and P .J. T. Leonard, "Astrophysics in 1993" section 3 (The Evolution of Stellar Rotation Rates and Activity). Publications of the Astronomical Society of the Pacific **106**, 1 (1994).

R. Cavallo et al. "An Upper Limit to Coronal X-rays from Single Magnetic White Dwarfs" Journal of Astrophysics and Astronomy **14**, 141.

AND FOR THE HISTORY, G. Verschuur, **Hidden Attraction: The History and Mystery of Magnetism**, Oxford University Press, 1993. Once, long ago, there was also a wonderful book called **Soul of Lodestone**, but I have no idea who wrote it or how to find it, now that my father's copy has disappeared.