MAGNETIC WHITE DWARFS WITH STRONG FIELDS

AND THE ORIGIN OF MAGNETISM IN WHITE DWARFS AND NEUTRON STARS

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Work in progress at Steward Observatory covering three aspects of magnetism in degenerate dwarfs is reviewed. First, the identification of the Minkowski bands in Grw + 70° 8247 with Zeeman transitions in hydrogen. Second, a determination of field strengths in the more strongly magnetic white dwarfs. Third, some observations and speculations concerning the origin of white dwarf and neutron star magnetic fields.

1) Grw + 70° 8247. (Work in collaboration with Kieth Hege, Jim Liebert and Peter Stockman). The strange bands in the brightest magnetic degenerate Grw + 70° 8247, the sharpest of which are at 3650, 4135, and 5855Å, have been a mystery since their discovery 40 years ago by Minkowski (1938). Many identifications have been suggested: with helium (Greenstein and Matthews 1957); with molecular helium (Angel 1972, Mullan 1971); and with Zeeman shifted atomic helium (Landstreet and Angel 1975). Recently Angel (1978) suggested that the λ5855 line was the $2s_0$-$3p_0$ transition of hydrogen which becomes stationary with wavelength at 5855Å for field strengths in the range 1.8 - 3.5 x 10^8 G. Further comparison of the wavelengths predicted by Praddaude's (1972) calculations of energy levels with Oke's (1974) multichannel spectrophotometry confirm that all the Hα subcomponents which are stationary or only weakly field dependent at fields near 2-3 x 10^8G are present in the data. We identify the edge at 6800Å with the 2s -$3p_{-1}$ transition, the absorption up to 7200Å as the $2p_{+1}$-$3d_0$ and $2p_{-1}$-$3d_{-2}$ transitions, and the absorption at 8500Å with the $2p_0$-$3d_{-1}$ transition.

No calculations are yet available of the n = 4 levels in such strong fields, but by extrapolating from the $2p_0$ and $3p_0$ levels, we expect the $2s_0$-$4p_0$ transition to become stationary with wavelength at around 4150Å at field strength B = 2.5 x 10^8G and thus to be the origin of the λ4135Å feature. Similarly the 3650Å feature can be identified with a stationary wavelength in the $2s_0$-$5p_0$ transition. Members of the $2s_0$-np_0 series all reach a limiting blue wavelength at around the same field strength because of a feature in the $2s_0$ energy level.

Since the hydrogen spectrum accounts for the wavelength, shape and location of the five strongest features in Grw + 70° 8247, we feel we have at last the correct identification. Given that the surface fields

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are in the range ~1.8 - 3.5 x 10^8G, we notice that the cyclotron frequencies ω_c lie right in the optical spectrum, corresponding to wavelengths in the range 3000-6000Å. No theoretical calculations of the polarization have been made for this case where $\omega \sim \omega_c$. Previous discussions of photospheric polarization have been in the approximation that $\omega_c \ll \omega$, (See Landstreet's review in these proceedings, also Angel 1977). The polarimetric observations of Grw + 70° 8247 show strong linear polarization as well as circular polarization. The wavelength dependence from .3 - 1.1μ has been measured by Landstreet and Angel (1975). The linear polarization is strong in the ultraviolet with constant position angle of 20°, is weak from .5-.7μ, and then is strong in the near infrared at constant position angle 110°. The 90° swing in angle occurs in the region of the cyclotron frequency, and is very likely associated with it. We can draw the analogy with a driven harmonic oscillator, which responds in phase for applied frequencies below the resonant frequency, out of phase for frequencies higher than resonant. In terms of quantum mechanics, optical frequencies below the cyclotron frequency excite only $\Delta m = 0$ transitions, which are oppositely polarized to the $\Delta m = 1$ transitions excited by frequencies higher than ω_c. The importance of the swing in linear polarization is that it gives us a way to measure the field strength in other magnetic white dwarfs where Zeeman features are not present or not identified (see below).

For frequencies much larger than ω_c the polarization effects will be in the low field limit of quasi-longitudinal propagation (circular dichroism, no significant linear polarization). This domain is below the ultraviolet atmosphere cut-off for Grw + 70° 8247, but can be explored with the space telescope. For optical frequencies much less than ω_c the propagation is quasi-transverse (linear dichroism, no significant circular polarization). We appear to be entering this domain at 1μ in Grw + 70° 8247, where the circular polarization has dropped to ~2%, while the linear polarization is ~7%.

2) Field strengths of GD229 and LP 44-113. (Work in collaboration with John Landstreet). These two white dwarfs are the only others known to show linear polarization. We have measured the wavelength dependence from 0.3 - 1μ, again using the multichannel spectrophotometer at the Hale telescope. In GD229 the position angle of linear polarization is constant from 0.4 to 1.1μ, but it begins to rotate below 4000Å, and the strength is dropping. The mean cyclotron frequency probably corresponds to a wavelength of 2500Å or a field strength of 4 x 10^8 G, the strongest field yet determined for a magnetic white dwarf. The circular polarization is very small at 1μ ($\omega \ll \omega_c$) but rises towards the ultraviolet, as expected. The strong absorption features in the spectrum of GD229 (Liebert 1976, Greenstein and Boksenberg 1978) do not match Hα components at 4 x 10^8 G, and are thus likely to be features in the helium spectrum which are, like the features in Grw + 70° 8247, stationary or only moving slowly with field.

In LP44-113 the position angle of polarization is constant from the UV through 8000Å but there is an indication, from the Palomar data and new measurements by Stockman, of rotation at 1μ. These data suggest a field strength of ~ 1.2 x 10^8 G, but more observations are needed. There are no absorption features in the spectrum, except for a very broad depression from 4400-6300Å.

3) <u>The Progenitors of Magnetic White Dwarfs and Pulsars</u>.- (Work in collaboration with Peter Stockman). Only a small percentage (~5%) of white dwarfs are strongly magnetic. The remainder show no signs of magnetism, with upper limits of a few kG in some cases. What factor determines the presence or absence of magnetism? The properties of magnetic white dwarfs and neutron stars are in some ways strikingly similar (same total flux threading the stars, same maximum angular momenta). It is tempting to speculate that the magnetic white dwarfs have followed a similar evolution to the pulsars, except that for some reason there was no final collapse of the magnetized degenerate core.

The theory of stellar evolution indicates that neutron stars have high mass progenitors, and so one can imagine that the magnetic white dwarfs are 'near miss' pulsars, with progenitors of not quite high enough mass to form neutron stars. Ruderman and Sutherland (1973) have suggested that the magnetic field in both types of object could be generated during convective carbon burning. We have tested this hypothesis by searching for magnetism in white dwarfs with known high mass progenitors - those found in clusters with high turn-off masses by Romanshin and Angel (1979). The KPNO 4m telescope was used to measure circular polarization in four of these rather faint ($V = 20$) objects. No positive detection was made above the errors from photoelectron statistics, which ranged from 0.25 - 0.5%.

While not conclusive, these results suggest that progenitor mass is not the determining factor for the occurrence of magnetism. We consider here an alternative factor, the presence of a strong field in the interior of the progenitor. We note that the field strengths (10^8G) in the more strongly magnetic white dwarfs and the values inferred for their progentiors may well be high enough to resist convection, so flux conservation would then be at least self consistent.

The birth rate of magnetic white dwarfs of about 5×10^{-14} pc^{-3} yr^{-1} must equal the death rate of the progenitors. Angel, Landstreet and Borra (1979) have pointed out that the death rate of Ap and Bp stars, the only main sequence stars with detectable surface fields, has approximately this value. Landstreet and Borra find that more than half of these stars have fields in excess of five hundred gauss. We note also that the maximum flux found threading Ap stars and degenerates is about the same. While these agreements may be fortuitous, they are consistent with the simple minded idea that non-magnetic white dwarfs are formed from the stars which show no fields, and the magnetic white dwarfs are formed by flux-conserving collapse of magnetic Ap stars. The implication is that the stars are like pieces of iron in that the observed external field tells you what the magnetization is inside. This is not required by theoretical considerations. Shielding of internal fields by surface currents is possible in main sequence stars and in white dwarfs if they rotate fairly fast (Moss 1979). Furthermore, convection may remove or create moderate magnetic fluxes during white dwarf formation. Nevertheless we find attractive the idea that white dwarfs conserve and show the magnetic flux of Ap progenitors.

We now return to the similarity of magnetic white dwarfs and magnetic neutron stars. If their evolutionary histories are similar and are as suggested above, then we must postulate that the pulsars' progenitors are also Ap (or Bp) stars, and that factors other than magnetism, such as mass or spin, determine whether there is collapse to a neutron star. There is

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now observational evidence that mass alone does not determine the final evolutionary fate of stars. On the one hand arguments from the pulsar birth rate (which is about the same or less than that of magnetic white dwarfs) and from the scale height of young pulsars suggest that many stars of mass less than $4M_\odot$ become pulsars (Taylor and Manchester 1977), though this is not a very secure conclusion (Arnett and Lerche 1978). On the other hand, the presence of white dwarfs in young open clusters shows that stars of mass at least $5M_\odot$ and probably $7M_\odot$ can become white dwarfs (Romanishin and Angel 1979). While factors such as binary evolution also spoil a simple correspondence between stellar mass and final evolution, the observations suggest that magnetism of an Ap or Bp progenitor may be the determining factor in the evolution of both magnetic white dwarfs and pulsars.

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