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White dwarfs in the 1990's*

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Abstract. White dwarfs are the last evolutionary phase in the lives of stars that begin with up to about eight times the mass of our sun (8 $M_{\odot}$). Their unique property is that the force of gravity is balanced not by ordinary gas pressure but by the pressure of degenerate electrons. The numbers of white dwarfs in our inventories have grown from three in 1926 to many thousands, both single and in binary systems. With the increase has come better understanding, but also a gradual expansion of the population over a wider and wider range of masses, temperature, magnetic field strengths, surface compositions, and other measurable quantities. Some of these confirm earlier predictions; others stretch the associated physics. We explore here the last decade of increased knowledge of white dwarf properties and their relationships with other parts of astronomy.

Key words : white dwarf, cataclysmic variable, gravitational redshift, Type Ia supernova, spectral type, model atmosphere

1. Historical Introduction

White dwarfs joined the subject matter of observational astronomy in 1914, when Walter S. Adams (1915) succeeded in exposing a spectrogram in which most of the light came from Sirius *comes* (now called Sirius B) while the two stars were close to their maximum separation. He found the companion to be about as blue (hence about as hot) as the primary, leading to a very small radius and very large density. The first important theoretical step was the recognition by R. H. Fowler in 1925 that matter at the implied density must be degenerate in the Fermi-Dirac sense (Fowler 1926). The relativistically correct theory was, of course, one of the many contributions of Chandrasekhar (1931a, 1931b, 1935).

In 1926, there were precisely three white dwarfs known, the companions of Sirius and of 40 Eridani and van Maanen's star (Russel, et al. 1926). They had, however, already been placed at the end point of stellar evolution on the basis of their faintness and high density (Eddington,

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* Dedicated to the memory of Prof. Wilhelmina Iwanowska, who died as it was being written

1926), (and also, it must be admitted, on the basis of an erroneous picture of stellar evolution, called the giant and dwarf theory). Indeed white dwarfs were the only recognized end point for stellar evolution until the discovery of pulsars in 1967-68.

Adams was generally thought to have confirmed the large densities (that is, large ratio of mass to radius) by a measurement of the gravitational redshift of Sirius B (Adams, 1925). His value of 19 km/sec was very much what was expected at the time. It is, however, too small by a factor of more than three, apparently because his spectrogram was badly contaminated by light from Sirius A. (There is a considerable literature on this subject). Later efforts were not much more successful (the next apastron passage was not until 1965), and several attempts to get a gravitational redshift for 40 Eri B led also to smallish numbers (correctly; it is a low-mass white dwarf, we now know) (Popper, 1954). One major telescope (the 200") and a social revolution (women at the California Institute of Technology) later, there were nearly 100 gravitational redshifts (Greenstein & Trimble, 1967; Trimble & Greenstein, 1972), most apparently slightly too large, for reasons that are still not entirely understood (Bergeron et al. 1991).

About two dozen white dwarfs were known by the time the conference on white dwarfs and novae took place in Paris in 1939 (Shaler 1941). This was, inevitably, the last major astronomical gathering for a number of years and was also the place where Eddington and Chandrasekhar aired most vigorously their divergent views on the propriety of combining quantum mechanical and relativistic considerations.

Surveys for stars of large proper motion by Willem Luyten, Gerard Kuiper and others had raised the inventory to several hundred stars by the mid-1960s (Greenstein et al. 1965), and nine spectral types were recognized (Greenstein 1960), differing apparently in both temperature of the stellar surface (anything from more than 20,000 K to less than 6,000 K) and in surface composition (hydrogen vs. no hydrogen being the sharpest distinction). A demonstration, based on velocities of the white dwarfs relative to our local standard of rest, that they occur in both population I (young) and population II (old) also dates from this period (Iwanowska & Opaska-Burricka 1962).

The most mysterious of all the spectral types, a few stars with a strong feature at 4135 Å began to yield its secrets in 1970, with the discovery of circular polarization in these stars in an amount implying surface magnetic fields of 10^7 Gauss and more (Kemp et al. 1970). Remarkably, such strong magnetic fields break up all the degeneracies of the hydrogen atom and send the line components wandering this way and that in wavelength. The mysterious features are plain old Balmer lines (Greenstein et al. 1985), with Lyman lines wandering around the ultraviolet.

Two reviews, derived from proceedings of conferences held when the confirmed number of white dwarfs was about 2000, provided considerable additional historical material (Greenstein 1987, Trimble 1987). That by (Greenstein 1987) is particular dense in early references. The latter review has a whole page missing (on magnetic fields of neutron stars), and nobody except the author seems ever to have noticed.

Approaching the modern era, we find another set of reviews and conference proceedings (Weidemann 1990; D'Antona & Mazzitelli 1990; Chanmugam 1992; Evans & Wood 1996) with background information about single and binary white dwarfs.

2. White dwarf masses

The single most important fact about any star is its mass. This determines its luminosity, size, temperature, lifetime, potential nuclear reactions, and ultimate fate. Even after a star has reached the white dwarf (WD) end point, its mass matters in several ways. First, if we ever find any above the Chandrasekhar limiting mass (1.44 $M_\odot$ for helium ranging down to 1.2 $M_\odot$ for iron interiors), then many fundamental ideas are in deep trouble, and we would be forced to consider either a very strange equation of state for WD matter or variants of general relativity (Cochero 1998). The greatest threat to the Chandrasekhar limit has always been the white dwarf component of the old nova T CrB, for which early work gave a mass of 2 $M_\odot$ or more. Newer data have supposedly resolved the problem (Kric et al. 1998) but "certainty" that the mass must be less than 1.44 $M_\odot$ has to some extent been folded into the analysis.

White dwarf masses also affect their cooling rates (important for determining the ages of various stars and stellar populations and discussed below) and our understanding of earlier evolutionary phases as a function of initial mass, since these must produce white dwarfs of the masses we see in clusters whose ages we measure from other indicators (Frantzman & Pyleva 1998; Umeda et al. 1999), as well as matching the average mass of about 0.6 $M_\odot$ (Homier et al. 1998). Finally, for the moment, the average is an important input to estimating the total density of stellar matter in the disk of our galaxy and so the additional amount of non-stellar stuff needed to match dynamical estimates (dark matter), and, conversely, as it were, the amount of gas that gets fed back into interstellar material as the WD forms.

The three traditional binary systems, 40 Eridani, Procyon, and Sirius yield masses of 0.43, 0.62 and 1.05 solar masses. Procyon was the most uncertain of these, but has now been pinned down to about 3% (Irwin 1992). Thus the real spread is obviously considerable. The first extensive survey of gravitational redshifts implied an average mass of 0.75 $M_\odot$ (Greenstein & Trimble 1967; Trimble & Greenstein 1972). The best modern value is 0.56-0.60 (Bergeron et al. 1991; Homier et al. 1998), but these numbers come from analysis of colors and line profiles (that is, surface gravitational accelerations) rather than orbits or redshifts, and so are somewhat model dependent.

The largest mass found has crept gradually upward with time, primarily because more stars have been examined. These numbers also come from spectroscopic values of surface gravity plus some assumption about that mass-radius relation. G35-26 weighed in at 1.2 $M_\odot$ (that is log g a bit in excess of 9) in 1991 (Bergeron et al. 1991) in nearly a dead heat with GD 50 (Thejll et al. 1990), which might have been a bit more massive, but was also more difficult to interpret, because of its atmosphere of helium and carbon rather than hydrogen. PG 0136+251 and PG 1648+441 brought us above 1.2 $M_\odot$ (Schmidt et al. 1992). Both have strong magnetic fields (as do about 10% of single white dwarfs in general). Additional examples of large mass and field together suggest that the correlation is a real one. A later analysis of the second PG star pushed it above 1.3 $M_\odot$, and perhaps revealed the error bars associated with the method (Wolff et al. 1995).

The current record holders fall at 1.43 ± 0.06 $M_\odot$ and 1.35 $M_\odot$ (Vennes et al. 1996; Ferrario et al. 1997), The latter is also distinguished by a strong magnetic field (450 Mega Gauss (MG)), rapid rotation (period = 725 seconds), and a cooling age considerably less than that of a nearby companion white dwarf. It has, that is, the hallmarks of a recent merger of two lower-mass stars (and with a slightly larger total mass might have spawned a supernova explosion, of which more later). These two stars, at least, tresspass upon the mass territory occupied by neutron stars that we see as pulsars in binary systems, and whose masses are therefore very accurately measured (Thorsett & Chakraborty 1999). The overlap is of considerable interest for our understanding of stellar deaths. There is apparently something besides core mass (rotation? initial composition ? magnetic fields?) that tells a star how to die.

The least massive white dwarf is less interesting physically. Very light single ones would be surprising, since they should come from stars of initial mass so small that they have not yet had time to complete their nuclear lifetimes. Comfortingly, the smallest measured surface gravity, log g = 6.67 (M = 0.16 $M_\odot$) belongs to the close companion of a neutron star (millisecond pulsar J 1012+5307). It has undoubtedly been robbed by its heftier neighbour at several stages (Vankerwijk et al. 1996). The less hefty of the white dwarf pair GP Comae is probably even more emaciated (Marsh 1999), though only the ratio is measured (at 0.02) and further erosion is currently underway. The end point is likely to be a single, low-mass star.

3. Surface and interior compositions

Spectrograms of the first three confirmed white dwarfs all showed rather blue continuua crossed by a few, very broad, Balmer hydrogen lines and nothing else. Both the broadness and the fewness result directly from the very dense atmospheres. Pressure broadening of the hydrogen atomic levels is already large for n = 2, and by n = 8 or 9 the levels overlap, blurring the lines together. The "nothing else" in visible wavelengths means that these stars, called spectral type DA (by analogy with ordinary A-type stars whose strongest spectral features are Balmer lines), have surface layers of rather pure hydrogen.

It was already realized at the time of the Paris conference that white dwarfs could have no hydrogen in their interiors (it would explode, nova-fashion) and soon after recognized that whatever H was there would, in any case, float to the surface because of the very strong gravitational fields (Schatzman 1949). The hydrogen layer is typically quite thin, perhaps not more than 10^{-12} $M_\odot$ (Barstow et al. 1994). Nor is it absolutely pure. Unpolluted, hot hydrogen is very transparent to ultraviolet and soft X-rays. The continuum emission is not as strong as it should be if the photons were escaping directly from deep layers, and the ultraviolet contains absorption lines due to as many as 12 heavy elements in addition to helium, in some stars (Vennes et al. 1996), though the abundances are still very small. DA white dwarfs remain the commonest sort, and all the others are sometimes just called non-DAs.

The next most abundant element in the universe is helium, so we are not surprised that the next most common classes of white dwarfs have atmospheres in which it is the dominant element. Helium is even more difficult than hydrogen to excite to a level where it can absorb visible photons. Thus, while hot, helium surface WDs display recognizable absorption features and are called type DB (again by analogy with ordinary B-type stars with strong neutral helium lines), the cooler ones have no conspicuous features at all and are called DC (for continuum). Ultraviolet spectra reveal that some of these also actually have small complements of heavier elements.

Since white dwarfs have no internal energy sources and live on stored kinetic energy, hot automatically means young, and indeed the hottest white dwarf types, called D0 and DA0 (by analogy with ordinary type 0 stars with HeII lines) have not yet had time for the hydrogen and helium to separate out and show spectral features of both (Barston & Hubeny 1998). There are in fact no true DAs above a surface temperature of about 80,000 K. Curiously, there is an intermediate temperature range (30 – 45,000 K) where helium-dominated atmospheres are very rare.

Because DC has been pre-empted for "continous" spectra, stars with strong carbon lines are called C2 or λ 4670 stars. Other recognized categories are DF (with ionized calcium lines) and DG (with both calcium and iron). The names are again analogous to normal, cooler stars with metal lines. Van Maanen 2, one of the first single white dwarfs identified is of this rare, DG, type and is probably very massive.

A group of very hot, often pulsating, stars for which the prototype is PG 1159 are dominated by the next most abundant elements, carbon and oxygen, presumably both because they have lost most of their hydrogen and helium and because gravitational settling has not yet had time to reveal what is left. Occasional stars defy the conventional types, like the relatively cool (5400 K) LHS 1126 which revels in simultaneous helium, molecular hydrogen, and molecular carbon (Bergeron et al. 1994).

Just how much physics do we need to account for all the types; and is our inventory complete ? A good deal, it seems, and probably not. The inventory includes (a) gravitational settling as already mentioned, (b) mass loss (which is a low-density, high-speed continuation of the process that bared the cores in the first place), (c) levitation of particular elements and ions by radiation pressure in strong absorption lines, (d) mixing upward of interior material (typically carbon) by a thin convection layer, and (e) accretion of gas from the general interstellar medium (or from a companion, a special case discussed below).

These processes work on a range of initial conditions set by the precursor stars (called post-asymptotic giants and nuclei of planetary nebulae) which have finished their nuclear evolution and blown off their outer layers. These precursors have a range of surface gravities (hence efficiency of gravitational settling) and of surface composition (hence raw materials to work on). Clearly, what we see is a result of some balance among all the processes working on the ensemble of initial conditions (Bergeron et al. 1996; Unglaud & Bues 1998; Pena et al. 1998; Moeller et al. 1998; Hrivnak & Kwok 1999). A few additional processes, like diffusive hydrogen burning, have been proposed at various times, and clearly the last words have not been said on the problem of accounting for the full richness of white dwarf surface compositions and their statistics. Another indicator that we may not have considered everything that can modify the composition is that some nominal DAs have more atmospheric opacity at ultraviolet wavelengths (where heavy elements typically enter) than appears in the standard models (Madej 1998).

Cataclysmic variables or binaries are pairs consisting of a white dwarf with a main sequence (hydrogen-fusing) or occasionally red giant companion, in which gas is flowing from the surface of the companion onto the white dwarf. Flare-ups of the systems occur when the accretion rate increases (dwarf novae) or when the accumulated hydrogen is sufficient to explode (classical novae). Nor surprisingly, the surface composition of these WDs is largely that of the transferred gas (Jordan et al. 1994; Schmid 1994; Long & Gilliland 1999). Post-nova, composition returns briefly to normal, since the explosion removes the accreted material (Kato & Hachisu 1994). Similar pairs where mass transfer has not yet begun also exist, though they are sufficiently difficult to recognize that only about 15 are known (Burleigh et al. 1997). The prototype is V471 Tauri, and the total inventory of CVs amounts to about 1020 (Downes et al. 1997).

Calculations of stellar evolutionary sequences predict three possible interior compositions for the remaining core that becomes a white dwarf. These are (a) nearly pure helium (for core mass less than about 0.4 $M_\odot$, which never becomes hot enough for the triple alpha reaction to produce Carbon), (b) mostly carbon and oxygen (for core masses of about 0.4 to 0.9 $M_\odot$ left from stars of 1 to 5 or so $M_\odot$ that burned helium but nothing beyond), and (c) mostly oxygen, neon, and magnesium (for the largest core masses, left by stars that experienced some heavy element burning, but not enough to produce a Chandrasekhar-mass iron core that would collapse to a neutron star).

We have already seen that white dwarfs exist in each of the mass ranges. Direct evidence for interior composition comes only in cataclysmic variables, where material is transferred from one star to the other and / or blown off in a nova explosion, so that we can study it as diffuse gas. All three sorts of compositions are seen. Extra CNO, from white dwarfs with the intermediate composition, characterize the commonest kind of nova, both in the Milky Way and in the Large Magellanic Cloud (Schwarz et al. 1998). The sort enhanced in ONeMg are over-represented in surveys because they tend to be brighter and to recur more often (Starrfield 1993). No nova ejecta suggest an underlying helium star, which is as it should be; the extra CNO or ONeMg mixed into the accreted envelop is needed to make the explosive reactions occur. Thus we recognize the helium white dwarfs only in the rare case where a pair of then are so close together that interior matter is being spilled into the space between them for us to study. At least four such systems are known, where the star gas is nearly pure helium. All are of very low mass as expected (Solheim 1992). Occasional events have intermediate composition, like a 1993 nova in which only oxygen seems to have been greatly enhanced (Salama et al. 1999).

Unfortunately, repeated exchange of material between the stars in cataclysmic binaries prevents our associating particular interior compositions or current WD masses securely either with an initial main sequence star mass or even with an initial core mass. Indirect evidence for internal composition of single WDs can, however, be derived from the precise relationship of radius to mass, because the heavier elements have fewer electrons per unit mass to contribute to pressure support. Recent data from the HIPPARCOS astrometric satellite confirm that Sirus B is massive (1.17 $M_{\odot}$) but, surprisingly, indicate a radius appropriate to a carbon or carbon-oxygen interior, rather than heavier elements (Holberg et al. 1998). One must again conclude that mass is not quite the only thing that tells stars what to do. At the other end of the composition spectrum, we can say only that single white dwarfs exist at less than 0.45 $M_{\odot}$ (Homier et al. 1998; Maxstead & Marsh 1998) and that there are mechanisms to produce them from initially more massive stars that begin life with brown dwarf or planetary companions and have time to complete their evolution in the age of the universe (Nelemans & Tauris 1998).

4. Surface temperatures and luminosities

While the most massive white dwarfs are arguably the most interesting, for surface temperatures and luminosities it is the smallest values that concern us most, both because they are the oldest and because, it turns out, the hardest to calculate or model. Historically, the problem of old, cold, dim dwarfs came to seem exciting when it was necessary to invoke a condensed matter process, the crystallization of C and O nuclei (which locks up a good deal of energy in zero point fluctuations and so accelerates the fading) to account for numbers and luminosities (Mestel & Ruderman 1967).

At the present time, the folklore says that (a) we are still rather puzzled by the total absence of WDs fainter than 10^{-5} $L_{\odot}$ and are not quite sure whether it means that none is old enough to have faded further or that some physics is still missing from the calculations, but (b) the situation for higher luminosities and temperatures is more or less under control. It is, however, worth noting that the temperature scale vs. observed colors for DAs in the range 50–70,000 K has just undergone a major revision as a result of recognition of the effects of previously-neglected atmospheric metals (Barstow et al. 1998). Other temperature ranges will probably also require adjustment but the work hasn't been done yet. A second worrisome feature is that, in the supposedly well understood age range near 10^9 yr, white dwarf sequences found with HST in a couple of open star clusters yield ages inconsistent with those found from other indicators for the same clusters, no matter which set of models you use (Von Hippel 1995).

The youngest, hottest white dwarfs form a continuum with the post-asympototic gaint branch stars and nuclei of planetary nebulae that are their ancestors (at least most of the time Rauch 1999). The current record is very close to 100,000 K. It is, not surprisingly, of type DO and was the first single white dwarf recorded as an X-ray source with ROSAT (Fleming et al. 1994; Werner 1994). X-rays from magnetic cataclysmic variables are, in contrast, common, because accretion provides a continuous supply of coronal gas. The hottest magnetic white dwarf is a relatively chilly 50,000 K (Barstow et al. 1995). The difference could be merely a statistical effect (large temperatures and strong magnetic fields are both rare, so the overlap could be by chance zero in present samples) or an indicator that magnetic fields in white dwarfs take some time to develop, come to the surface, or otherwise manifest themselves Sect. 5). None of the single magnetic stars has been seen as an X-ray source, although fields are of direct relevance to the maintenance of coronae in main sequence stars.

Returning to the dark and dreary, we note several items. First, because there is a real range of white dwarf masses and radii, the faintest star found to date (ESO 439-27 with $M_V = 17.4$, T=4560 K, and log g = 9.40) (Ruiz et al. 1995) is not the same as the coolest, at 3900 K (Hambly et al. 1997). Second, there remains a considerable range of cooling calculations in the literature, leading to inconsistent results and with no very good way to choose among them (Garcia - Berro et al.; Benvenut & Alphaus 1999). It has been known for some time that the discrepancies arise from different choices of input physics (compositions, masses, conductive opacities, thicknesses of surface hydrogen and helium layers, and so forth), not from careless computing.

The real bell-ringer in the last year or two is, however, a third item, the recognition of the effects of molecular hydrogen in dense, cool atmospheres. One indeed expects some molecule formation below 5000 K or so, but since H_2 is made of two identical atoms, it should have no strong dipole transitions to absorb radiation. The surprise is that some stellar atmospheres are dense enough for pressure-induced dipoles to become appreciable, leading to absorption in the usual near infrared bands. The result is IR colors that look bluer than previously found (Hansen 1998; Saumon & Jacobson 1999). The same thing happens in very cool main sequence stars and brown dwarfs, which also have dense atmospheres (Chabrier & Baraffe 1997). Not only will these color differences affect our interpretation of the coolest, reddest stars found so far, but they mean that searches for these stars may not, so far, have been appropriately tailored. Thus the apparent absence of white dwarfs fainter than $10^{-5}\ L_\odot$ (and the rarity of very faint M dwarfs and brown dwarfs) may not be representative of the real world. Stay tuned for further developments on this news story!

5. Magnetic fields and rotation

These topics belong together at least tentatively for three reasons. First, the white dwarfs for which we can set some of the most stringent limits on rotation rates include the magnetic ones. Second, both angular momentum and magnetic flux are widely supposed to have been conserved through evolution from progenitors; and, third, if some of the fields are really induced by dynamos, then field strength might be associated with rotation rate.

The recognition in 1968 that pulsars are rotating neutron stars with magnetic fields near 10^{12} G prompted the first serious searches for white dwarf fields (though the idea goes back to P.M.S. Blackett in 1947). Because white dwarf lines are already very broad, Zeeman broadening is not a promising technique, though the absence of quandratic Zeeman shifts in many DA spectra says that most such dwarfs have fields much less than those detected through circular polarization (Kemp et al. 1970) and that the true distribution must be bimodal, with the second peak well below 1 MG (Trimble 1971). Crudely, most of the confirmed fields have log B = 6.5 to 8.5 and the limits are log B $\leq$ 5-6.

As in the case of WD masses and temperatures, the range of measured fields has gradually expanded at both ends, with lower and upper values of 350 Kilo Gauss (kG) (Schmidt et al. 1992) and 500 MG (Jordan 1992) in 1992 (the year of the discovery of the first magnetic white dwarf in a double degenerate pair) (Bergeron et al. 1993). All came from polarization measurements. The minimum directly measured value dropped to 100 kG in 1994 (Schmidt &

Smith 1994), with a contemporaneous indirect value fo 1300 G implied by mode analysis of the pulsating DB white dwarf GD 358 (Markiel et al. 1994). V 471 Tauri, the prototype of non-interacting binaries, also hits 100 kG, based on different indirect argument pertaining to inhibition of accretioin onto the star by the "propeller effect" (Sion et al. 1998). And three additional small (but non-zero)field values of 30-50 kG, derived again from analysis of pulsation modes have appeared subsequently (Koester et al. 1998)

At the high field end, the correlation with large mass persists (Ferrario et al. 1998) a connection that may also be present among the magnetic white dwarfs in CVs(Cropper et al. 1998). Strongly magnetic DBs had seemed until recently to be very rare, but now number about a half dozen (Reimers et al. 1998), a reasonable ratio to the 50 or so magnetic DAs (Putney et al. 1995). One might suppose that the 100 MG field of LHS 2229 was somehow at least partially responsible for its strange, strong absorption feature coming from C_2H or some other C-H bond, but at least one non-magnetic star displays the same bands (Schmidt et al. 1999) Contrarily, RE J0317-853 has a λ 1160 line that is normally a forbidden transition and possible in its atmosphere only because the very strong magnetic field (up to 800 MG) induces an electric field capable of distorting the atoms (Burleigh et al. 1999).

Magnetic fields in the white dwarfs in cataclysmic variables are both commoner (perhaps 30% of the systems rather than 5%) and confined to a much narrower range of strengths, with a maximum of 7080 MG for RX J1938.4–4623 (Schwope et al. 1995). The reason for the difference is not understood, though one's thoughts naturally spring to the fact that the sub-day orbit periods of these systems frequently force co-rotaion of the white dwarf, which might otherwise rotate in anything from seconds to centuries.

White dwarfs are indeed typically slow rotators compared to their break-up periods of 10's of seconds (even the "fast rotator" mentioned in Sect. 2). Supporting evidence is of three kinds. First, many DAs have H-alpha lines with very sharp cores, from which it can be deduced that v sin i (the projection of the rotation speed along our line-of-sight) is not more than 5-15 km/sec, and could be much less (Koester et al. 1991). This implies rotation periods of an hour or more; in contrast, neutron stars are found essentially up to the stability limit at 1.5 msec. Second, analysis of pulsation modes of the subset mentioned in the next section leads to a good fit to the various periods without any allowance for rotational splitting (Koester et al. 1991). Third, in the case of the stars with strong magnetic fields, one can look for rotation as periodic changes in line profiles and positions. Some show periods of a few hours to a few days. In others, there have been no changes over many years, leading to lower limits of decades for the rotation period. The current record for a suggested actual measurement is 80 years for GD 229 (Beryogin 1995).

An interesting interaction between magnetic field and angular momentum occurs among the cataclysmic variables. A plot of number of systems vs. orbit period shows a statistically significant minimum for periods between 2 and 3 hours. This can probably be understood in terms of the effects of magnetic braking of the systems when the companion star becomes completely convective and the usual dynamo mechanism (which operates at the base of the convective envelope) can no longer give the companion a magnetic wind to carry off angular momentum. Support for the general scenario comes from a systematic difference in WD masses above and below the gap. The long period ones average to 0.80 $M_\odot$ and the short period ones to 0.69 $M_\odot$ (Smith & Hillon 1998).

Systems where the white dwarf is itself highly magnetized have a very different period distribution. They come with both long and short periods (Buckley 1998 a, b) but a sizable number are smack, dab in the middle of the gap (Craig et al. 1996; Burwitz et al. 1998; Reimers et al. 1999; Greiner & Schwarz 1998).

Rotation per se is less interesting for the CVs. Orbit and rotation periods show up separately in the light curves when they are different. The strongly magnetized white dwarfs are always synchronized. Those with no detectable field never are. And the intermediate ones come in the middle (Campbell & Schwepe 1999) (hence names like polars and intermediate polars).

What are the origins of white dwarf angular momenta and magnetic fluxes? Those who first contemplated the problem (Ginzberg 1964; Woltjer 1964) envisioned conversion of both from main sequence stars with rotation periods of days to months and fields of 10–1000 G, as are seen for many stars. Of late, and perhaps by analogy with similar recent proposals for neutron stars, the rotation has been blamed on asymmetric ejection of planetary nebulae and winds (Spruit 1998) and the fields on in situ dynamos (Schmidt & Grauer 1997).

6. Pulsating white dwarfs

Astronomers are familiar with an instability strip that stretches diagonally across the Hertzsprung-Russell (or color-magnitude) diagram from reddish supergaints to white (A-type) main sequence stars. All stars within it display some degree of pulsational variability, from factors of a hundred in brightness over months for Cepheid variables to a few percent in a fraction of a day for main sequence stars. This strip crosses the location of white dwarfs. Indeed most of the WDs within the zone are periodic variables, though the pulsation modes are not the radial ones you might have expected. The stars are called zz Ceti variables, named for the prototype.

This primary, well-known instability strip arises because hydrogen is just being ionized as you look beneath the photosphere, and the ionization zone acts as a tap or faucet, stopping radiation until all the atoms are ionized, then letting it flood out. Most stars have atmospheres where 90% or more of the atoms are hydrogen. So do the DA white dwarfs. But there are also WDs with atmospheres consisting mostly of helium (the DBs) and mostly of carbon and oxygen (the PG 1159or GW Vir stars). These turn out to have their own instability strips at higher temperatures, driven by the ionization of their dominant elements. The first zz Ceti was an accidental discovery in 1968. Pulsating DBs were predicted in 1981, and the first one found the next year. The pulsation of GW Vir was again an accidental discovery in 1979, but with theoretically-motivated follow-up work. The stars, especially the third GW Vir, class, can display simultaneous excitation of several modes.

As is the case with the ranges of properties mentioned in other sections, as the numbers of pulsating WDs known has increased, so has their variety and the extent to which they test existing theories. An important long range goal is to see period changes of the sort you expect as the stars age and become fainter and cooler, thus testing calculations of cooling. Such changes have not yet been unambiguously seen, but we come closest for the GW Vir stars because they are the hottest.

In current inventories, the zz Ceti stars are the commonest, with about 30 known (Giovannini et al. 1998). This makes them the commonest sort of variable star in the galaxy, since the sample is drawn from only very nearby stars. Periods range up to about 20 minutes, and one star has been found to display 19 simultaneous non-radial modes (Kleinmann et al. 1998). Modern calculations match the observed correlations of periods and their changes with surface temperature (Goldreich & Wu). The continued non-detection of radial modes of any order remains puzzling.

The binary helium white dwarf AM CVn also varies in brightness with multiple modes, but the underlying mechanism is different from that of the pulsating DBs (Dreizler & Heber 1998). A physically different sort of pulsation, driven by the burning of residual hydrogen in the very hot DAO stars has been looked for in nine examples, but not seen in any of them (Handler 1998). They were definitely expected.

The instability strips for types DA and DB are fairly clean, with sharp edges in temperature between pulsators and non-pulsators. But the GW Vir strip includes about equal numbers of each. The non-pulsators have detectable nitrogen, as well as carbon and oxygen, in their atmospheres, and this is apparently to blame (Dreizler & Heber 1998). Hydrogen, in contrast, is not an objectionable pollutant. The star HS 2324+3944 displays about 20 frequencies between 300 and 1000 μHz despite its atmospheric hydrogen. They are attributed to non-radial pulsation, rotation, and linear combinations thereof (Silvotti et al. 1999).

The star RX J 2117+3412 (whose name indicates that it was originally spotted as interesting because it emits soft X-rays) has apparently increased its effective temperature up to 170,000 K between 1992 and 1995, landing outside the nominal PG 1159 instability strip, but without losing its variability. It may constitute the first example of yet another class of pulsating white dwarf (Feibelman 1999).

Mechanisms of light variability in cataclysmic variables are both numerous and complicated, but relate primarily to gas transfer from the companion star to a disk orbiting the WD and to instabilities in that disk, not to pulsation of the white dwarf itself.

7. The interface between white dwarfs and the rest of the universe

More, and more varied, topics fall in this area than can be arranged in any linear sequence, so let's start with the most exciting. Searches for gravitational lensing of stars in the Magellanic Clouds are finding four or five events per year. If the lenses are in the extended (dark) halo of the Milky Way, then their average masses are 0.3 - 0.5 $M_\odot$. They cannot be low-mass, hydrogen-burning stars, or we would see them. Neutron stars and black holes can be excluded for other reasons. The remaining alternative is very old, cold white dwarfs. If these descend from the same range of stellar masses that make such WDs now, then the implications for the chemical evolution of the Galaxy, its past luminosity, and the current location of most of the baryons in the universe are very exciting (Chabrier 1999). In fact, they may be so exciting (in the sense of massive production of carbon, making the Milky Way enormously bright in the past compared to the galaxies we see at large redshift, and so forth) as to be impossible (Von Hippel 1998).

At the frivolous end of the spectrum of astronomical significance, we find the Seyfert galaxy NGC 6814, whose apparent 3.4 hour periodic variability was actually the orbit period of a cataclysmic binary superimposed on its image (Staubert et al. 1994).

Somewhere in between come white dwarfs as X-ray sources. We have already mentioned soft X-rays from very hot single stars. In addition, the specific class called supersoft X-ray binaries (with most of the known ones in the Magellanic Clouds because our own galactic disk is not very transparent below 1 keV) seem to be systems with rapid accretion onto a white dwarf from a normal companion, with the energy released more or less continuously, rather than in nova explosions (Hughes 1994; Kubo et al. 1997; Smith et al. 1998; Mitch 1998; Van Teeseling & King 1998; Greiner et al. 1999).

Binaries containing white dwarfs and more or less like CVs were suggested some 20 years ago as the most likely identification for the fainter X-ray sources in globular clusters. (The brighter ones have neutron stars as the accreting component). CVs near us are too faint in X-rays to correspond to the sources seen in the more distant clusters, but many people working on the problem still believe that something like CVs are the best bet (Grindlay et al. 1995). On the plus side is the fact that known cataclysmics in old, open clusters like M67 are X-ray sources with intermediate luminosities (Belloni et al. 1998). On the minus side is the demonstrated deficiency of optically-confirmed CVs in globular clusters compared to what you would expect from calculations of binary star evolution (Shara et al. 1996). The unique X-ray source RX J1914.4+2956 with a regular period of 569 sec may be both the first X-ray source associated with an orbiting pair of WDs and the shortest-period binary system found anywhere so far (Cropper et al. 1998).

A very old problem to which white dwarf binaries may or may not be the answer is that of identifying progenitors of Type Ia supernovae. These are the SNe with no hydrogen in their spectra, old stars for their neighbours, evidence for the production of 0.2 - 0.8 $M_\odot$ of iron from explosive burning of carbon and oxygen, and applicability to problems involving cosmological distance scales. Theoretically, the best ancestor one can think of is a pair of white dwarfs with an orbit period less than about 12 hours (so that they will spiral together in the age of the universe when angular momentum is lost in gravitational radiation) and a combined mass greater than the Chandrasekhar limit (so that they will explode when they meet). Unfortunately, among known WD pairs, the vast majority of massive systems have long orbit periods, and the short period systems have total masses much less than M_{ch} (Finley & Koester 1997). At any given instant, the candidate pool will have in it a system or two of large total mass but unknown period (Vennes et al. 1999) and one or two of short period but slightly uncertain future (Koen et al. 1998). Ordinary CVs have two disadvantages as SN Ia progenitors, (1) there is usually hydrogen around and (2) nova explosions generally remove more material than was accreted since the last explosion, so that the WD masses go down rather than up with time. Pairs with helium star donors may solve the first problem; recurrent novae or symbiotic stars may be exceptions to the second problem. No systems belonging to both types are known.

White dwarfs can be expected to fit into our general schemes of stellar life cycles. The standard picture of stellar evolution has asymptotic giant branch stars shedding their envelopes, illuminating them as planetary nebulae (as soon as the bared core is hot enough - 50,000 K or so – to ionize the surrounding material), and then dying as white dwarfs after the nebula has dissipated and the stars cooled below where they can maintain the ionization. This is not necessarily true. One model of chemical evolution suggests that only about 30% of 1 $M_\odot$ stars illuminate PNe en route to becoming WDS, and from the other side a surprising fraction of hot DB stars show no trace of a nebula (Allen et al. 1998; Rauch 1999). One might be able to make an indirect check by comparing birthrates of PNe and WDs in the solar neighbourhood, but both are probably too uncertain to decide whether the numbers are the same or different, let along which is bigger. A recent estimate puts the WD birthrate at 4.6×10^{-13} WD/yr/pc^3 in our neighbourhood (Smith 1998). This corresponds, very roughly, to one per year in the Galaxy.

The mere detection of a white dwarf in certain contexts is important, because it says that the progenitor star did not become a Type II (core collapse) supernova and leave behind a pulsar, a neutron star, or a black hole. When there are coeval stars around (cluster members or binary companions) whose masses one can measure, then the presence of the WD sets a limit on the minimum mass needed to produce a Type II SN, pulsar, etc. This minimum is both rather uncertain and quite dependent on the initial composition (and perhaps other characteristics) of the parent stars (Mowlavi et al. 1998)., but 9 ± 2 $M_\odot$ covers many cases. A brand new form of this constraint has appeared, with the discovery of the first two white dwarfs in binary systems with stars as hot, massive, and short-lived as spectral type B (Vennes et al. 1997; Burleigh & Barstow 1999). The more traditional case is the presence of WDs in moderate-age star clusters like the Pleiades (which has only one) and Hyades (which has eight, but where you would expect more like 28; it is also deficient in WD companions to stars of about 2 $M_\odot$ (Boehm-Vitense 1995)). The youngest, and so most informative, cluster with apparent white dwarf members is NGC 6623, where, unfortunately, it is not clear that most of the six recognized WDs actually belong to the cluster (Reimers & Koester 1994).

Finally, we come to another important issue, the age of the oldest stars, which sets a lower limit to the age of the universe that must be permitted by the cosmological parameters. These oldest stars are undoubtedly the ones in globular clusters in the halos of our own and other galaxies. Ages are normally determined from the stars that have just exhausted the hydrogen fuel in their cores and so are beginning to change their luminosities and temperatures away from those of main sequence stars, on the way to becoming red gaints. The oldest white dwarfs in the same clusters would provide an enormously important and independent confirmation that we are doing the right thing. Unfortunately, these WDs are too faint for their colors (hence temperatures and ages) to bē measured accurately even with the Hubble Space Telescope. Progress so far includes (1) having found the bright (young) end of the WD sequence in three globular clusters and learning that their colors, brightnesses, and numbers are about what you would expect (F. Paresce et al. 1994; Elson et al. 1995; Richer et al. 1995) and (2) having found the faint end of the WD sequence in the old, open cluster M67 and concluding that the implied age disagrees with that found from stars leaving the main sequence (von Hippel et al. 1995).

Meanwhile, the oldest white dwarfs in the solar neighbourhood (disk of the Milky Way galaxy) have also been dated from how much they have cooled. The primary goal is to understand the relationship between halo star formation (clocked with the globular clusters) and disk star formation (clocked with the oldest nearby stars) in the Milky Way and other galaxies. At the present time, 11±3 Gyr covers all the recent determinations for disk white dwarfs, but this is not accurate enough to decide whether or not there was a latency period between the end of halo star formation and the onset of disk star formation (García- Berro et al. 1999; Benvenuto & Alphaus 1999; Leggett et al. 1998; Winget 1997)

8. Looking ahead

White dwarf experts naturally expect that important new results will continue to appear across the full range of observable parameters and theoretical connections. My own prejudice is that the most important issues are (a) finding the pairs that give rise to Type Ia supernovae (or be sure they do not exist), (b) finding the oldest WDs in the oldest globular clusters and settle whether they are 9, 13, or 17 Gyr old (this also requires additional work on cooling curves at the faint end (Hansen & Phinney 1998). (c) sorting out what the MACHOs (MAsive Compact Halo Objects that act as gravitational lenses for stars in the Magellanic Clouds) really are, and (d) improving models of galactic chemical evolution and measurements of stellar statistics to the point where it is clear whether the white dwarfs fit in with everything else we think we know.

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