14. STELLAR AGES

NEW MODEL ATMOSPHERE ANALYSES OF COOL WHITE DWARFS: A REVISED LUMINOSITY FUNCTION AND CONSTRAINTS ON THE AGE OF THE GALAXY

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1. Abstract

We have obtained new photometric and spectroscopic data for a large sample of cool white dwarfs. These data have been analysed with state-of-the-art model atmospheres and effective temperatures and atmospheric compositions have been determined (Bergeron, Ruiz & Leggett 1997). Radii and masses have also been obtained for those stars with accurate parallax measurements. These high quality data and models allow us to produce an improved cool white dwarf luminosity function based on the Liebert, Dahn & Monet (1988) proper motion sample. The turn-over seen at the faint end of this luminosity function, combined with theoretical cooling sequences, enable us to constrain the age of the local region of the Galaxy.

2. Introduction

The majority of stars will evolve into electron-degenerate white dwarfs and then cool to invisibility. The accurate trigonometric parallaxes determined by the Naval Observatory Flagstaff Station (described earlier in these proceedings) produce a well-defined degenerate sequence in color-magnitude diagrams, with a sharp terminus (Figure 10 of Monet *et al.* 1992). White

T.R. Bedding et al. (eds.),
Fundamental Stellar Properties: The Interaction between Observation and Theory, 429–432.

dwarfs are most likely to be composed of carbon/oxygen cores, with surface envelopes of helium and sometimes hydrogen. Trace metals can be present. They cool at approximately constant radius while their surface composition can evolve in ways which are currently not fully understood.

Models of the cooling scales of white dwarfs show that even stars aged 10 Gyr will be visible, implying that the observed luminosity function of white dwarfs can be used to constrain the age of the local region of the disk. Liebert, Dahn & Monet (1988, hereafter LDM) produced an observational luminosity function that was used by Wood (1992) to derive an age for the disk of 8-11 Gyr. Observational uncertainties made up nearly half of the uncertainty in this age. The LDM sample suffered from uncertainties due to the unknown chemical composition of the coolest stars in the sample, as well as defiencies in the model atmospheres available at that time. The few models that were available did a poor job of reproducing the observed flux distributions (e.g. Leggett 1989).

3. Improvements to Model Atmospheres and Observations

Since 1989 my collaborators and I have been obtaining high quality optical and infrared data for a large sample of cool white dwarfs (Bergeron, Ruiz & Leggett 1997, hereafter BRL), while significant improvements have also been made to the model atmospheres (Bergeron *et al.* 1995). The improvements to the models include improved calculations of the collision-induced H_2 opacity, improved treatment of H_3^+ (important for H^- opacity), modelling of pressure ionization of He (important for He^- opacity) and more accurate line broadening calculations for $H\alpha$. Comparison with observation now shows excellent agreement (see BRL) although there are still some deficiencies. These are: theoretical treatment of pressure ionization of hydrogen; missing sources of UV opacity for the coolest hydrogen-rich white dwarfs; and an apparent 5% discrepancy in the absolute flux calibration.

4. Derived Parameters

The observed energy distributions are compared to model fluxes and T_{eff} and the angular diameter are derived, with an initial assumption that the surface gravity $logg = 8.0$. If the parallax is known, the radius R is determined from the angular diameter. Knowing R and T_{eff} the evolutionary models of Wood (1995) are used to derive the mass M. The implied value of $g = GM/R^2$ is compared to the initial value and the process iterated until these agree. If the parallax is unknown then $logg = 8.0$ is adopted.

The uncertainties in the derived parameters are typically: 150K for T_{eff}, 0.06 $M/M_\odot$ in mass, and 0.10dex in $logg$. Varying the mass of the surface envelope used by the evolutionary models leads to Δ M $\sim$ 0.03 $M/M_\odot$ and

$\Delta log g \sim 0.02$dex. For H-rich atmospheres the photometry and Hα profiles constrain the amount of He present to $< 50\%$, which has a negligible effect on the derived parameters. For He-rich atmospheres we can constrain the amount of H present to $< 1\%$ however this has a large effect on the derived parameters: this amount of H would lower T_{eff} by 250K, and lower *logg* by 0.15dex, with an implied reduction in M of $0.10M/M_{\odot}$.

5. Implications for White Dwarf Evolution and Disk Age

A study of the chemical composition of our sample as a function of T_{eff} (or age) shows that for $6100K > T_{eff} > 5100K$ there is a significant lack of non-DA white dwarfs (i.e. stars not showing H features). We speculate that some combination of convective mixing of the (variable depth) outer layers, together with accretion of H onto a high-pressure He atmosphere (in such a way that H transitions are quenched), could produce this result.

We also find that the cooling curves of Wood, with a C/O core and thin He envelope, imply cooling ages for our sample of < 8 Gyr. To this can be added pre-PN ages of <2 Gyr. Uncertainties due to core composition and thickness of the outer envelope are ~2 Gyr.

We are able to improve the luminosity function (LF) derived by LDM as we have determined accurate stellar parameters for the stars in that sample. The earlier cooling curves by Wood, combined with the 1988 LDM results, implied an age for the disk of 8-11 Gyr. New models by Wood (with C/O cores, thick surface layers and new opacities; Oswalt *et al.* 1996) compared to the 1988 LDM results imply a younger age of 7-9 Gyr. These models have also been compared to an observational LF based on white dwarfs in binaries (Oswalt *et al.*) to derive an age of ~9.5 Gyr. However this sample suffers from severe incompleteness and the data is insufficient to determine composition for the coolest stars. It is also difficult to obtain accurate photometry for small-separation binaries, such as the three faintest stars in their sample, on which the disk age hinges.

Figure 1 shows the LF derived for hot white dwarfs by Fleming *et al.* (1986, slightly revised by LDM), our redetermination of the LDM function, and a comparison to the latest theoretical LF by Wood. The error bars are derived by assuming that the uncertainty for each star equals the size of its contribution to the space density. We can constrain the disk age to 8±0.5 Gyr. Systematic uncertainties due to core composition and mass of the outer layers amount to 1–2 Gyr. Also, as described by Chabrier in these proceedings, there is the possibility that C/O separation occurs on crystallization of the older massive stars, releasing gravitational energy, and extending cooling times by a further 1–2 Gyr.

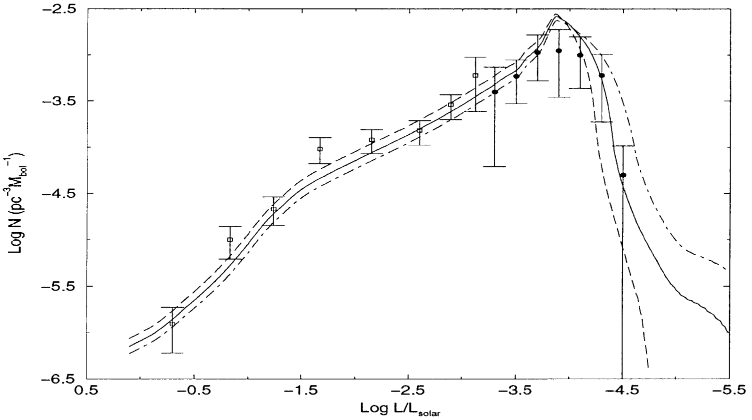

Figure 1. New luminosity function for the 8-tenths sample of LDM and theoretical curves from Wood (1996) for disk ages 7, 8 and 9 Gyr (left to right)

6. Conclusion

As the aim of this meeting is to discuss outstanding problems in stellar astrophysics, we close with a list of areas where further work is needed.

Problem	Solution?
UV opacity for $T_{eff} < 5300K$ DA's	Lyman edge pseudo-continuum
Trace H in high pressure atmospheres	H occupation probability
Chemical evolution	convective mixing mechanisms
Core composition, surface layer mass	pulsation studies
Observational improvements	data, parallaxes, flux calibration

7. References

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Discussion of this paper appears at the end of these Proceedings.