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The peculiar sdB NGC 6121-V46: A low-mass double degenerate ellipsoidal variable in a globular cluster

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Abstract. The variable sdB known as V46 in the globular cluster M4 has remained enigmatic since its discovery almost 10 years ago. We present here radial velocity measurements obtained from medium-resolution VLT/FORS2 spectra that show variations at twice the period of the luminosity changes. This implies that the system is an ellipsoidal variable. Unlike the other sdB binaries of this nature, the fundamental parameters of this star we derive suggest that it lies below the Zero Age Extreme Horizontal Branch. From the cluster distance and the gravity we determine the mass of V46 to be $\sim$0.19M$_\odot$. This is too low to sustain core helium burning. From the mass function we derive a lower limit for the companion of only 0.26M$_\odot$. We discuss the star's origin in the context of close binary evolution in the field and globular clusters.

Key words: stars: variable: general – stars: individual: NGC6121-V46

1. History and Motivation

It is now known that while the mass distribution of DA white dwarfs peaks at $\sim$0.6M$_\odot$, there is also a subset of objects with masses $\leq$0.46M$_\odot$ (Bergeron et al. 1992). Their low mass implies that they cannot ignite helium in their cores, and must have lost most of their envelope mass before reaching the tip of the red giant branch. The implication of this is that the stars must be in close binary systems, although recent results suggest that fewer than 50% show radial velocity variations (Napiwotzki et al. 2005).

There are two kinds of known binaries containing helium-core white dwarfs (HeWDs): double degenerate systems, typically containing two low-mass white dwarfs (e.g. Nelemans & Tout 2005) and millisecond pulsar (MSP) systems. In the former case the lowest mass HeWD companion known has 0.31M$_\odot$ (Marsh et al. 1995), while in the latter the masses are $\leq$0.2M$_\odot$ (e.g. Callanan et al. 1998).

Recent discoveries suggest a link between HeWDs and a small subset of sdB stars. As part of a program to measure radial velocities of sdBs, Heber et al. (2003) discovered that the apparently normal sdB HD 188112 lies below the Zero-Age Extreme Horizontal Branch (ZAEHB). The star's mass, determined from its trigonometric parallax, $T_{\rm eff}$ and $\log g$ to be only $0.24 \mathrm{M}_\odot$, is inconsistent with the lowest mass for the common envelope ejection model of Han et al. (2003). HD 188112 is a radial velocity variable with a minimum companion mass of $0.73 \mathrm{M}_\odot$, suggesting the primary is the progenitor of a helium core white dwarf, while the unseen companion is most likely a C/O white dwarf. Comparison with the evolutionary tracks of Driebe et al. (1998) supports this conclusion.

Since then, Liebert et al. (2004) have discovered another object lying below the ZAEHB. Comparison of the parameters of SDSS J123410.37-022802.9 (hereafter SDSS J1234) with the evolution tracks of Althaus et al. (2001) shows that this star has a mass in the range 0.18-$0.19 \mathrm{M}_\odot$. Note that the mass is dependent on the evolution models adopted. A higher mass is found ($\sim 0.23 \mathrm{M}_\odot$) for SDSS J1234 when it is compared to the Driebe et al. tracks.

Kaluzny et al. (1997) discovered intensity variations with amplitude $\sim 1.9\%$ and period 1.045 h in the star now known as V46 in NGC 6121 (= M4). The system was a puzzle from the beginning, with colours consistent with those of a cataclysmic variable, but no emission lines present in its spectrum. Mochejska et al. (2002) found that the spectrum is consistent with an sdB star. With the discovery of pulsations in sdB stars with periods of 0.75-2 hours (Green et al. 2003), it seemed possible that V46 was a member of this class. We therefore set out to clarify the object's nature.

2. Is it an EHB star?

A low resolution spectrum of V46 taken with the MMT was kindly provided by Janus Kaluzny. By means of Balmer line profile fitting we find $T_{\rm eff} = 16197 \pm 546\,\mathrm{K}$ and $\log g = 5.75 \pm 0.108$; the star shows no helium lines. We used Detlev Koester's DA white dwarf grid (Finley et al. 1997) to derive these parameters. When we examine the position of V46 in the $T_{\rm eff} - \log g$ plane (Figure 1), we find that it, like HD 188112 and SDSS J1234, lies below the ZAEHB. This means the star has not evolved via the EHB and strongly suggests that it too is the progenitor of a HeWD (similar to HD 188112).

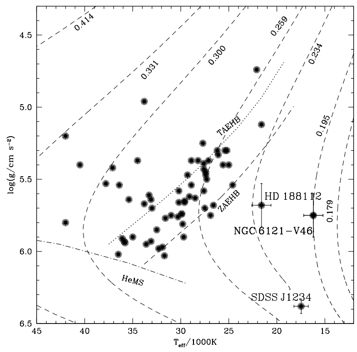

Fig. 1. Position of V46 in the $T_{\rm eff} - \log g$ diagram.

If we consider the distance to the cluster M4 (2.2 kpc – Rosenberg et al. 2000) and the surface gravity of V46, we find that it should have a mass of $\sim 0.19 \mathrm{M}_\odot$. In Figure 1 we show the post-RGB evolutionary tracks of Driebe et al. (1998) which suggest that V46 should have a mass of $\sim 0.195 \mathrm{M}_\odot$. This is very good agreement considering the uncertainties of the model physics, and is strong evidence that the star is a member of the cluster and not a foreground object. Using the VLT we have determined the nature of this system by measuring the radial velocity of V46.

3. The Nature of NGC 6121-V46

We obtained 81 spectra with resolution ∼2100 using VLT/FORS2 with the 1400V grating in service mode. The only line visible in the spectra is Hβ, and the resulting S/N per 4-minute exposure was 10-15. We measured the radial velocity of Hβ by cross correlation with a model spectrum at the temperature and gravity derived above. The velocity curve is shown at the top of Figure 2, while the power spectrum is shown at the bottom. It was calculated by fitting the curve with a range of periods using χ^2 minimisation. Based on this method, we measure the period and ephemeris to be HJD(T_0)= $2453134.496797 + 0.087159 \times E$, while the system velocity and semi-amplitude of the system are $\gamma = 31.3 \pm 1.6$ km/s and $K = 211.6 \pm 2.3$ km/s, respectively. Using this period and semi-amplitude we derive the mass function of the system to be $f(m) = 0.0855 \pm 0.0028 \mathrm{M}_\odot$. Taking the mass of the sdB to be $0.195\mathrm{M}_\odot$, the minimum mass of the secondary is $0.26\mathrm{M}_\odot$. We note that the period of the radial velocity variation is exactly twice that of the intensity variation, indicating that V46 is an ellipsoidal variable, similar to the previously known systems KPD 0422+5421 (Koen et al. 1998) and KPD 1930+2752 (Billéres et al. 2000; Maxted et al. 2000).

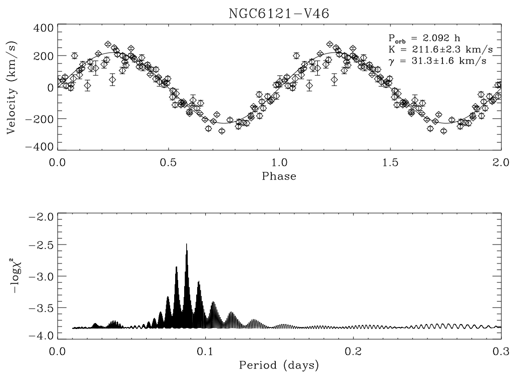

Fig. 2. Radial velocity curve and corresponding power spectrum of V46.

4. Light Curves

As well as a velocity curve, we have also obtained BVR light curves. These observations were made over April-June 2001 to search for oscillations in red giants in M4 (Bruntt 2003). They were obtained at the Danish 1.54m at La Silla, Chile with DFOSC. We have attempted to determine the inclination angle of the system using a light curve analysis similar to that used for the sdB HS 2333+3927 (Heber et al. 2004). No eclipses have been detected. Due to the low amplitude of the ellipsoidal variations the analysis is difficult. We kept the $T_{\rm eff}$ and mass of the sdB fixed at 16 200 K and $0.2\mathrm{M}_\odot$, respectively, during the analysis, but could not find a unique solution. Even fixing the mass ratio arbitrarily at, e.g. $q = 3.0$, does not help. The fits from all solutions appear identical and have very similar χ^2 values. There must be a lower limit for the inclination since at some angle the deformation of the sdB will no longer be visible. To find this limit, we first set $q = 6.0$ and then decreased it in steps of 1.0. Again no unique solution could be found, meaning that unfortunately the light curves cannot place any constraints on the system. Nevertheless we can conclude that the companion must be a white dwarf, because the variations are ellipsoidal in nature and there is no sign of a reflection effect. The latter would be expected if it were a low-mass main sequence star.

5. Implications

Despite not being able to constrain the inclination of the V46 system, we can still discuss the implications of its existence for close binary formation in globular clusters. Hansen et al. (2003) discussed low-mass HeWDs in globular clusters from a theoretical standpoint, and found that for the population of these stars in the core of NGC 6397 the companions are most likely C/O white dwarfs and not neutron stars. The likelihood of the companion of V46 being a neutron star is not high, since the inclination angle of the system would have to be $\leq 26°$, and there has been no detection at radio wavelengths of any neutron star in M4 other than PSR B1620-26 (Lyne et al. 1988). We suggest therefore that V46's companion is either a C/O or HeWD. At the most probable inclination of 52° the mass of the companion is $\sim$0.40$M_\odot$, making it an object with a helium core. We also point out that V46 lies outside the central part of M4; more massive objects are expected to settle towards the core of a globular cluster.

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