# The Multiple Star 14 Aurigae

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**The multiple star 14 Aurigae (= ADS 3824) contains five visual members, of which A and C (both of them single-lined spectroscopic binaries) form a physical system. Extreme ultraviolet observations reveal a hot white dwarf superposed on 14 Aur C. Ultraviolet spectroscopy reveals that it is a distant companion to the optical spectroscopic binary, but that is a physical member of the system. Capitalizing on the fact that the visible component of 14 Aur A, KW Aur, is somewhat evolved, and is both an ellipsoidal variable and $\delta$ Scuti pulsator, we are able to model this quintuple system, obtaining both an evolutionary age for the system and a cooling age for the white dwarf, also masses for all five components, orbital inclinations for the two spectroscopic binaries, and an improved distance estimate to the system. Our results provide empirical values of the pulsation constants of KW Aur, and an estimate of the initial as well as final mass of the white dwarf.**

**Keywords:** Stars: Binaries – Stars: Individual: 14 Aurigae – Stars: Variables: $\delta$ Scuti – Stars: White Dwarfs

## 1 Introduction

Among the brightest extreme-ultraviolet objects discovered by *ROSAT* (Pounds *et al.* 1993) is RE J0515+324, a source which is coincident with the bright ($V = 7.95$) F4V star ADS 3824 C = 14 Aur C = HD 33959C. Ultraviolet observations (Webbink *et al.* 1992; Hodgkin *et al.* 1993) revealed a hot DA white dwarf with no obvious stellar spectral features other than Ly$\alpha$, with the F4V star increasingly prominent at $\lambda > 1700$ Å. Subsequent spectroscopic observations of the optical counterpart (Webbink *et al.* 1992; Emley *et al.* 1993; Tokovinin 1997; Vennes, Christian & Thorstensen 1998) revealed that it is a single-lined spectroscopic binary with a 3-day period and mass function $f(m) = 0.00763 M_\odot$.

The relatively early spectral type and long period of this system (compared with normal cataclysmic binaries) raised the possibility that it could be an early-type pre-cataclysmic binary. Systems of this type have long been predicted by common envelope models for the formation of cataclysmic binaries (*e.g.*, de Kool 1992; de Kool & Ritter 1993; Politano 1996), but in the detached state preceding mass transfer from optical component to the white dwarf, the latter star is overwhelmed at visible wavelengths by the former, rendering such systems undetectable from the ground. When they reach mass transfer, systems with such relatively massive donors should generally transfer mass on the thermal time scale of the donor, achieving mass transfer rates high enough to stabilize hydrogen burning on the accreting white dwarf. In this case, the system does not suffer ordinary nova or dwarf nova outbursts. If the mass transfer rate is not too high, the white dwarf will remain at an effective temperature and luminosity characteristic of planetary nebulae as it accretes most of the donor star mass. This is the favored model for supersoft X-ray sources (van den Heuvel *et al.* 1992).

An alternative possibility is that this system could be a long-sought remnant of Algol-type evolution. Such systems would consist of an intermediate-mass main sequence star with a low-mass (helium degenerate) white dwarf companion. Since the late stages of Algol-type evolution proceed on the nuclear time scale of the giant-branch donor, and the radius of that donor (and hence the orbital period of the binary) is a very sensitive function of its core mass, one expects to find the white dwarf masses strongly correlated with the remnant orbital period. At a period of 3 days, a white dwarf mass of only $\sim 0.2\mathrm{M}_\odot$ is indicated. Although Algol types are the most numerous of known eclipsing binaries, their post-mass-transfer counterparts have eluded discovery for the same reasons described above for early-type precataclysmic binaries: their white dwarf components are overwhelmed at visible wavelengths by their nondegenerate companions. Indeed, since an F4V companion is nearly as late in spectral type as Algol evolution will permit within a Hubble time scale, much earlier type post-Algol systems (or those with white dwarf components of much greater cooling age) would probably be undetectable even in the vacuum ultraviolet.

## 2 Observations

In the expectation that 14 Aur C would conform to one or the other of these two models, six spectra were obtained in early 1996 of the white dwarf component at Ly$\alpha$ using the Goddard High-Resolution Spectrograph (GHRS) aboard the Hubble Space Telescope (HST). These spectra were arranged in phase to sample both conjunctions (1 spectrum each) and both quadratures (2 spectra each). Since the white dwarf can scarcely be much more massive than the F4V star, its orbital semiamplitude should exceed that of the F4V star ($K_{\mathrm{F4V}} = 29.1$ km s$^{-1}$). In the event, *no* orbital motion was detected to a 2-$\sigma$ limit of $\sim 12$ km s$^{-1}$. Despite its coincidence with the F4V star (within the $3''\!.4 \times 3''\!.4$ acquisition aperture of HST, the hot white dwarf identified with 14 Aur C is *not* the spectroscopic companion of the F4V star.

Although 14 Aur C diplays no detectable foreground reddening, interstellar absorption lines due to N I $\lambda\lambda$ 1200, 1201, O I $\lambda$ 1302, and Si II $\lambda\lambda$ 1260, 1304, 1527, as well as an absorption component in Ly$\alpha$, are clearly present in co-added high-dispersion IUE spectra (Holberg, Barstow & Sion 1998). This co-addition also reveals the presence of Si IV $\lambda\lambda$ 1393, 1402 resonance lines in absorption — lines which must clearly originate in the atmosphere of the white dwarf. The emergence of this feature at the same wavelength in IUE spectra widely separated in orbital phase not only confirms conclusively that the white dwarf is not the spectroscopic companion of the F4V star, but provides a superior measure of the apparent radial velocity of the white dwarf itself. We shall see below that the velocity difference between the white dwarf (henceforth 14 Aur Cc) and the F4V spectroscopic binary (henceforth 14 Aur Cab) is entirely consistent with the gravitational redshift of this white dwarf. That is, it is a distant, physical third component of 14 Aur C. It has subsequently been resolved, at an angular distance of $2''\!.006$ from 14 Aur C, in an HST snapshot program (Barstow *et al.* 2001).

## 3 Analysis

Although 14 Aur C has confounded expectations that it would provide valuable new insights into close binary evolution, its membership in a hierarchical multiple affords a valuable opening to explore several important problems in stellar evolution. Aitken (1932) catalogued four visual components in this system (ADS 3824ABCD), to which we may add a faint interstitial fifth component discovered by Hodgkin, *et al.* (and labeled by them 'D'). Of these five visual components, 14 Aur A and 14 Aur C form a physical system: they share nearly the same proper motion and systemic radial velocities, the differences ($4.01 \pm 0.39$ mas yr$^{-1}$ in proper motion and $0.94 \pm 0.11$ km s$^{-1}$ in radial velocity) being entirely consistent with their relative orbital motion about a common center of mass. The remaining visual components are field stars, B and D discrepant in both proper motion and radial velocity, the fifth component (which we here label E) too bright in view of its very red color to be a plausible physical member.

The brightest visual component, 14 Aur A, is of considerable interest in its own right, as a single-lined spectroscopic binary ($P = 3^{\mathrm{d}}\!.79$; Harper 1916) in which the visible component (14 Aur Aa = KW Aur) is both an ellipsoidal variable and a $\delta$ Scuti variable (Fitch & Wiśniewski 1979). Detailed abundance studies of KW Aur (Kurtz 1976; Rachkovskaya 1988, 2000) reveal a pattern of rare earth enhancements characteristic of $\delta$ Delphini stars, overlying an essentially solar iron abundance. It is clearly somewhat evolved, hence its A9IV $\delta$Del spectral classification in the Bright Star Catalog. Its pulsation properties were studied exhaustively by Fitch and Wiśniewski, who isolated three modes at frequencies 11.35231 d$^{-1}$, 10.35910 d$^{-1}$, and 11.3323 d$^{-1}$, the latter two rotationally split. Fitch and Wiśniewski identified them as $(\ell,m)$ = (1,+1), (1,0), and (1,–1) modes, respectively. They hypothesized that, because of tidal distortion of the pulsating component, the principal pulsation axis resides along the line of centers of the binary, rather than along the rotation axis. Our own exhaustive analysis of 335 available radial velocities of KW Aur confirms both the pulsation frequencies found by Fitch and Wiśniewski, and the dependence of apparent pulsation amplitude on orbital phase expected from their mode identifications.

The array of observational constraints which can be brought to bear on the quintuple system 14 Aur Aab+Cabc makes it an attractive object for modeling. Those which we have employed include the trigonometric parallax; $V$ magnitudes and $B-V$ colors of Aab and Cabc; projected rotation velocities and orbital semi-amplitudes of Aa and Ca, photometric semi-amplitude of the ellipsoidal variation of Aab, measured in the Strömgren $b$ band; flux distribution of Cc, characterized by the effective temperature and solid angle best fitting it for a reference model atmosphere at $\log g = 8.0$; and the apparent velocity difference between Cc and the center of mass of Cab, interpreted as a relative gravitational redshift, with a small (but quantifiable) contribution to its error budget arising from orbital motion of Cc with respect to Cab.

A key ingredient in modeling the 14 Aur system is the evolved nature of component Aa (KW Aur), which allows us to estimate the age of the entire system, and fix its components along a common isochrone. The values of observational constraints enumerated above are then calculated theoretically *ab initio* from a set of model parameters which includes: the distance to the system, the individual masses of each of its five components, the orbital inclinations of the two spectroscopic binaries Aab and Cab, the evolutionary age of the system, and the cooling age of the white dwarf. For our evolutionary models we adopted the solar-metallicity grid of models by Schaller *et al.* 1992 for $M \geq 0.80\mathrm{M}_\odot$ and Charbonnel *et al.* 1999 for $M < 0.8\mathrm{M}_\odot$, with Kurucz (1993) model atmospheres; and carbon-oxygen white dwarf cooling curves from Wood (1995), with Wesemael *et al.* (1980) hot DA white dwarf atmospheres. The details of these computations, and sources of the observational constraints they seek to fit, will be described in detail elsewhere. Here it suffices to say that the solution involves a complex, but numerically well-behaved, nonlinear least-squares minimization for 13 observables with 10 model parameters. Originally, the foreground reddening, $E(B-V)$, was included as well, both as an observable (from the ultraviolet flux distribution) and as a model parameter, but has proven consistent with $E(B-V) = 0$ in every case.

Optimization of the model parameter set yields two formal solutions (Table 1) for the age and structure of the 14 Aur system. Solution 1 places KW Aur at its entry into the Hertzsprung gap, in the rapid expansion toward the giant branch following core hydrogen exhaustion (see Figure 1). Solution 2 places it in the terminal main sequence phase of its evolution, at the point where core convection has disappeared and the star begins to contract briefly as the last vestiges of hydrogen are burned out of its fossil convective core. Both solutions yield quite satisfactory fits to all observable parameters (Table 2), making it difficult to ascertain which is correct. Solution 1 produces a better fit, but corresponds to a significantly more rapid evolutionary phase (as reflected in its significantly smaller formal uncertainty in the system age, $t_{sys}$), and hence it is *a priori* less likely. Resolution to this ambiguity could come from reproducing the pulsation spectrum of KW Aur, but we lack pulsation constants appropriate to the evolutionary models employed here. The mean pulsation frequency for the three identified surface modes is consistent in both solutions with pulsation constants for the $(n, \ell) = (4,1)$ mode ($n$ being the radial mode number) calculated by Fitch (1981) using the old Los Alamos opacities. Detection of pulsation period derivatives could resolve the ambiguity, since the two solutions evolve in nearly opposite directions in the HR diagram. Detection of the period derivatives will however require extensive new photometric and perhaps spectroscopic time series.

Table 1: Model solutions

| Parameter | solution 1 | solution 2 |
|---|---|---|
| $d$ (pc) | 85.49 ± 2.71 | 87.40 ± 3.93 |
| $M_{Aa}$ ($\mathrm{M}_\odot$) | 2.237 ± 0.028 | 2.396 ± 0.096 |
| $M_{Ab}$ ($\mathrm{M}_\odot$) | 0.732 ± 0.041 | 0.777 ± 0.065 |
| $M_{Ca}$ ($\mathrm{M}_\odot$) | 1.387 ± 0.020 | 1.406 ± 0.030 |
| $M_{Cb}$ ($\mathrm{M}_\odot$) | 0.415 ± 0.030 | 0.421 ± 0.033 |
| $M_{Cc}$ ($\mathrm{M}_\odot$) | 0.691 ± 0.030 | 0.682 ± 0.034 |
| $\sin i_A$ | 0.472 ± 0.019 | 0.465 ± 0.024 |
| $\sin i_C$ | 0.703 ± 0.042 | 0.699 ± 0.044 |
| $\log t_{sys}$ (yr) | 8.905 ± 0.015 | 8.812 ± 0.057 |
| $\log t_{cool}$ (yr) | 6.490 ± 0.061 | 6.485 ± 0.062 |

# 4 Discussion

The success of theoretical models in satisfying all of the observational constraints provides a useful test of the robustness of those models, but the significance of our results transcends that elementary consistency check. The high precision which our solutions attain makes it possible to define empirically the individual pulsation $Q$'s of KW Aur within ~5%, making it a valuable standard against which to test pulsation theory, including tidal as well as rotational splitting. In addition, the second of the two solutions described above deserves special attention. Its existence and properties depend sensitively on the extent of overshooting during core hydrogen burning in KW Aur, which determines the redward extent of its main sequence evolution. With lesser overshooting (Schaller *et al.* adopt $d_{\mathrm{over}}/H_P = 0.2$), this solution quickly becomes unacceptable, as the evolutionary sequences never become as red as needed during core hydrogen burning; with greater overshooting, this solution bifurcates into two distinct solutions: one in which

Table 2: Model observables

| Observable | observed | | solution 1 | solution 2 |
|---|---|---|---|---|
| $\pi_{\rm trig}$ ($''$) | 0.01214 | $\pm$ 0.00117 | 0.01170 | 0.01144 |
| $V_A$ (mag) | 5.0047 | $\pm$ 0.0031 | 5.0047 | 5.0046 |
| $(B-V)_A$ (mag) | +0.2196 | $\pm$ 0.0041 | +0.2196 | +0.2196 |
| $\Delta b_A$ (mag) | 0.00400 | $\pm$ 0.00020 | 0.00398 | 0.00381 |
| $v_{Aa} \sin i_A$ (km s$^{-1}$) | 26.56 | $\pm$ 0.50 | 26.59 | 26.75 |
| $K_{Aa}$ (km s$^{-1}$) | 22.832 | $\pm$ 0.114 | 22.833 | 22.841 |
| $V_C$ (mag) | 7.9532 | $\pm$ 0.0267 | 7.9533 | 7.9545 |
| $(B-V)_C$ (mag) | +0.4147 | $\pm$ 0.0312 | +0.4146 | +0.4035 |
| $v_{Ca} \sin i_C$ (km s$^{-1}$) | 16.75 | $\pm$ 0.95 | 16.76 | 16.75 |
| $K_{Ca}$ (km s$^{-1}$) | 29.086 | $\pm$ 0.102 | 29.086 | 29.086 |
| $\log T_{e,Cc}$ (K) | 4.644 | $\pm$ 0.020 | 4.642 | 4.645 |
| $\log \Omega_{Cc}$ (sterad) | −22.417 | $\pm$ 0.011 | −22.414 | −22.420 |
| $v_{Cc} - v_{Cab}$ (km s$^{-1}$) | 32.01 | $\pm$ 4.08 | 32.47 | 31.53 |
| $\chi^2$ ($\nu = 3$) | | | 0.171 | 1.512 |

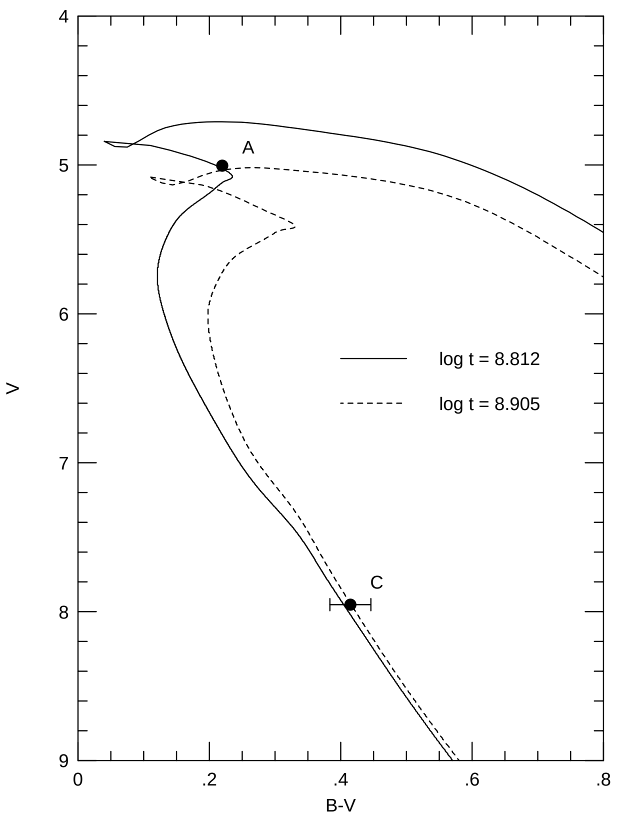


**Fig. 1**: Observational Hertzsprung-Russell diagram showing isochrones corresponding to both solutions. The observational points are not corrected for the contributions of the secondary (or tertiary) components.

KW Aur is still on the main sequence in convective core hydrogen burning, and a second solution, intermediate between this one and the Hertzsprung gap solution (solution 1), placing KW Aur in the relatively rapid phase of contraction as its radiatively-stable core approaches hydrogen exhaustion. Again in this instance, successful modeling of the pulsation spectrum of KW Aur will be key to resolving the ambiguities in its actual evolutionary status. With that resolution, it stands to constrain strongly the extent of core overshooting it has undergone.

Because we are able to determine an evolutionary age for the 14 Aur system, and a cooling age for its white dwarf component, 14 Aur Cc, we can secure an estimate of the initial mass of the white dwarf ($M_{Cc,0} = 2.455 \pm 0.030\,{\rm M}_\odot$ and $M_{Cc,0} = 2.644 \pm 0.118$ ${\rm M}_\odot$ for solutions 1 and 2, respectively), and add it to the handful of white dwarfs (the others all members of proper star clusters) for which such an initial mass-final mass relation can be determined empirically (Weidemann 2000). These estimates indicate that slightly less than half the total mass of Cabc was lost during the terminal evolution of component Cc. Depending upon the time scale for that mass loss, it could lead to a modest (factor of two) adiabatic expansion of the orbit of Cc about Cab (if it were slow compared with the orbital period of Cc about Cab), or it could launch Cc on a highly eccentric orbit (if rapid compared with the orbital period). Astrometric limits on the acceleration of the photocenter of Cabc, resulting from the displacement of its center-of-light from its center-of-mass, already demand that Cc lie either before or behind Cab in the plane of the sky, by a distance significantly greater than its projected separation, given the component masses derived in our two solutions. This suggests that the orbital period ratio among the visible components, i.e., $P_{Cabc+Aab}/P_{Cc+Cab}$, is probably $<10$, and may be sufficiently small to jeopardize the long-term stability of the multiple (Kiseleva, Eggleton & Anosova 1994; Eggleton & Kiseleva 1995), implying that Cc may not long survive as member of the 14 Aur system.

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