V605 AQUILAE: THE OLDER TWIN OF SAKURAI’S OBJECT

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ABSTRACT

New optical spectra have been obtained with VLT/FORS2 of the final helium shell flash (FF) star, V605 Aql, which peaked in brightness in 1919. New models suggest that this star is experiencing a very late thermal pulse. The evolution to a cool luminous giant and then back to a compact hot star takes place in only a few years. V605 Aql, at the center of the planetary nebula (PN) A58, has evolved from $T_{\text{eff}} \sim 5000$ K in 1921 to $\sim 95,000$ K today. There are indications that the new FF star, Sakurai’s object (V4334 Sgr), which appeared in 1996, is evolving along a similar path. The abundances of Sakurai’s object today and V605 Aql 80 years ago mimic the hydrogen-deficient R Coronae Borealis (RCB) stars, with 98% He and 1% C. The new spectra show that V605 Aql has stellar abundances similar to those seen in Wolf-Rayet [WC] central stars of PNe, with $\sim 55\%$ He, and $\sim 40\%$ C. The stellar spectrum of V605 Aql can be seen even though the star is not directly detected. Therefore, we may be seeing the spectrum of light scattered around the edge of a thick torus of dust seen edge-on. In the present state of evolution of V605 Aql, we may be seeing the not too distant future of Sakurai’s object.

Subject headings: circumstellar matter — stars: abundances — stars: AGB and post-AGB — stars: evolution — stars: individual (V605 Aquilae)

1. INTRODUCTION

In 1996, Sakurai’s object (V4334 Sgr) was discovered undergoing a nova-like outburst (Nakano et al. 1996; Benetti et al. 1996; Duerbeck et al. 1996). Subsequent observations showed Sakurai’s object to be a star at the center of an old planetary nebula (PN) A58, has evolved from $T_{\text{eff}} \sim 5000$ K in 1921 to $\sim 95,000$ K today. There are indications that the new FF star, Sakurai’s object (V4334 Sgr), which appeared in 1996, is evolving along a similar path. The abundances of Sakurai’s object today and V605 Aql 80 years ago mimic the hydrogen-deficient R Coronae Borealis (RCB) stars, with 98% He and 1% C. The new spectra show that V605 Aql has stellar abundances similar to those seen in Wolf-Rayet [WC] central stars of PNe, with $\sim 55\%$ He, and $\sim 40\%$ C. The stellar spectrum of V605 Aql can be seen even though the star is not directly detected. Therefore, we may be seeing the spectrum of light scattered around the edge of a thick torus of dust seen edge-on. In the present state of evolution of V605 Aql, we may be seeing the not too distant future of Sakurai’s object.

In this letter, we report new, more sensitive optical spectra of V605 Aql that allow us to estimate the present $T_{\text{eff}}$ and abundances of the star.

2. OBSERVATIONS AND ANALYSIS

New optical spectra of V605 Aql were obtained on 2001 June 16, 18, 20, and 26 using FORS2 on the VLT-UT4 with GRIS_300V, centered at 5900 Å, and the GG375 filter. The spectra have exposure times of 2698, 1799, 1147, and 2698 s, respectively. Sensitivity curves were determined for each night using lamp spectra and observations of standard ESO spectroscopic calibrators. Wavelength polynomial solutions for each of the V605 Aql observations were derived by extracting and matching calibration lamp spectra. Fifth-order polynomials were used to minimize the errors of the fit to the dispersion relation. The wavelength calibration is accurate to about 0.5 Å after using night sky lines for correcting the zero point. The flux calibration is good to about 10% for the stronger lines. An 8 pixel extraction was made, centered on the star. The background was fit and subtracted, and the four spectra were summed. The final spectrum is shown in Figure 1.

This spectrum is a great improvement on the spectra of Seitter and of Guerrero & Manchado, obtained in 1986 and 1993, respectively, which show only one stellar line, C IV $\lambda\lambda$5801–5812.
Seitter (1987b) also identified stellar features of O v, O vi, and He ii, although these lines are not evident in her published spectra. In our new spectrum, a number of broad stellar lines are visible in addition to the narrow emission lines from the PN. As noted previously, there is very strong emission at C iv λ5801–5812. Also strongly present are C iv λ4658, He ii λ4686, and C iv λ7724. He ii λ4411, C iv λ5471, and O v λ5590 also seem to be weakly present.

Our spectroscopic analysis utilizes the CMFGEN code (Hillier & Miller 1998), which solves the transfer equation in the comoving frame subject to statistical and radiative equilibrium, assuming an expanding, spherically symmetric atmosphere, allowing for metal line blanketing and clumping. The stellar radius is defined as the inner boundary of the model atmosphere and corresponds to Rosseland optical depth $\tau_{R} \sim 20$, while $T_{\text{eff}}$ is defined by the usual Stefan-Boltzmann relation. As discussed below, the apparent flux and reddening inferred from the observed spectrum are not indicative of their actual values so they cannot be used as constraints on the absolute stellar luminosity. Therefore, we adopt a value of $L = 10^4 L_\odot$ predicted by evolutionary models for the FF of V605 Aql. This assumption has negligible influence on the derived temperature or elemental abundances.

Our approach follows previous studies (e.g., Crowther et al. 2002, 2006) such that diagnostic optical lines of C iv λ5801–5812, and He ii λ4686 plus the local continuum allow a determination of the stellar temperature, elemental abundances, mass-loss rate, and wind velocity, for an adopted $L = 10^4 L_\odot$. The ratio of $C_{\text{iv}} \lambda 5801–5812/\text{He ii} \lambda 4686$ together with the absence of $O_{\text{vi}} \lambda 3811–3834$ indicate $T_{\text{eff}} = 95,000 \pm 10,000$ K ($R_e = 0.37 \pm 0.07 R_\odot$). A standard velocity law, $v(r) = v_\infty (1 - R/r)^{\beta}$, with $\beta = 1.5$, reveals a wind velocity of $2500$ km s$^{-1}$ and mass-loss rate of $1.3 \times 10^{-7} M_\odot$ yr$^{-1}$, assuming a wind clumping factor of $f = 0.1$ (an homogeneous model would be $f^{-1/2}$ higher). In the absence of any identifiable stellar hydrogen features, we assume hydrogen to be absent, and estimate the C and O abundances from $C/\text{He}$, $C_{\text{iv}}$, plus O/He $\sim 10$ by number using the optical recombination lines of He ii, C iv, and O ii to 5590, i.e., the mass ratio (%) is $\text{He : C : O} = 54 : 40 : 5$. The uncertainty in the He : C mass is $\sim$10–15%.

3. Discussion

3.1. A Thick Torus of Dust?

It seems strange that V605 Aql can be detected spectroscopically but cannot be imaged. The central feature seen in all images obtained since 1923 is not the star but the expanding central knot of hydrogen-deficient material that was ejected as part of the FF event. No sign of a stellar point-spread function is seen in the 1991 Hubble Space Telescope Faint Object Camera (HST FOC) image (Bond & Pollacco 2002). In 1991, the knot had a diameter of $\sim 0.75$ (Bond & Pollacco 2002; Clayton & De Marco 1997).

However, Seitter (1987a) suggested that there is a weak red stellar continuum in the spectrum of the central knot. A similar
red continuum is seen in our new spectra. The observed stellar continuum seems to have significantly less reddening than the star itself. Our models suggest a reddening of only $E(B - V) \sim 1.5$ mag is needed in order to fit the observed stellar continuum, assuming no nebular continuum contribution. Whereas, the extinction toward the star is estimated to be $E(B - V) > 3$, based on the star's invisibility on images (Clayton & De Marco 1997).

The observed faintness of V605 Aql could be accounted for if it is still the same absolute luminosity that it was in the 1920s, at a distance of about 3.5 kpc, with $A_V > 10$ (Clayton & De Marco 1997). If $A_V$ is this large, then little or no direct stellar light can reach us. But the dust may not have formed in a symmetric shell around the star. In V605 Aql, we could be viewing an optically thick torus edge on. In this geometry, light can escape perpendicular to the torus and scatter around the edge of the obscuring dust cloud. In this scenario, you would be able to "see" the stellar spectrum even though the star itself could not be imaged. The properties of the expanding knot surrounding V605 Aql are consistent with a bipolar structure with the rear side obscured by dust (Pollacco et al. 1992). Spectroscopic and imaging studies of two older objects (A30 and A78) thought to be FF stars, indicate that they may have an equatorial ring and polar nebular knots (Borkowski et al. 1994, 1995; Harrington et al. 1995).

Kimeswenger (2003) comments that the lack of scattered blue continuum argues against a torus-like structure. But the situation is quite complicated. If we are observing a stellar spectrum in scattered light, then neither the measured flux nor the reddening inferred from the spectra will reflect the actual values for V605 Aql. In this case, we are not seeing the light from the star directly transmitted through and reddened by a certain optical depth of dust in the shell. Rather, we are observing light from the star that travels along the poles of the torus where the extinction is significantly less but not zero. This light is then scattered by an unknown distribution of dust above the poles. The light will scatter preferentially in the blue, so it will affect the spectral energy distribution in the opposite sense to the reddening. The photons scattered in our direction will then pass through and be reddened by interstellar dust [$E(B - V) \sim 0.5$ at 3.5 kpc] along the line of sight (Clayton & De Marco 1997). Spectroplarimetry of V605 Aql could be used to help determine whether the torus model is correct and to distinguish what fraction of the spectrum is seen in direct and scattered light (e.g., Whitney et al. 1992, 1993).

### 3.2. The Evolution of V605 Aql

If we assume that the geometry outlined above is correct, then we have no direct measurement of the absolute luminosity of V605 Aql today. However, we can be guided by the early post-PF observations of V605 Aql and Sakurai's object, and by models of stars evolving through a very late thermal pulse (VLTP). Both Sakurai's object and V605 Aql are thought to be the result of a VLTP where the star experiences a helium shell flash while on the white dwarf cooling track (Herwig 2001; Lawlor & MacDonald 2003; Hajduk et al. 2005). Observations of V605 Aql and Sakurai's object are important in testing the predictions of these models concerning convection theory. The VLTP is required since the evolution of V605 Aql and Sakurai's object has been so rapid. In a late thermal pulse, which happens on the horizontal part of the post-AGB track, the return to the AGB takes 100–200 yr, which is much too long for Sakurai's object and V605 Aql (Herwig 2001).

Once the FF begins, both helium and hydrogen are being burned intensely (Herwig 2001; Lawlor & MacDonald 2003; Hajduk et al. 2005; Miller Bertolami et al. 2006). The outer hydrogen envelope is being mixed down convectively and burned. But the hydrogen is closer to the surface, so it is this energy that causes the first expansion and cooling of the star. It takes the star 5–10 yr to expand and cool back to the AGB. The star then moves back leftward in the H-R diagram toward hotter temperatures for 10–50 yr while contracting in size. Sakurai's object has shown an increase in ionization indicating that it may be heating up again after cooling and expanding back to the AGB (Hajduk et al. 2005; Kerber et al. 2002). Once there, the star begins a second loop where the energy from the helium burning causes the star to return to the AGB one last time, 250–500 yr later. During the first loop, the surface abundances of the star undergo large changes. A series of high-resolution spectra obtained in 1996 show the abundances of Sakurai's object changing on a timescale of weeks. In particular, the abundance of hydrogen was dropping accompanied by a rise in carbon and s-process elements. (Asplund et al. 1999). It is likely that V605 Aql is finishing the first rapid loop of the VLTP and has evolved more or less horizontally across the H-R diagram and today has $L \sim 10^4 L_\odot$ similar to its luminosity in the 1920s (Lawlor & MacDonald 2003; Hajduk et al. 2005). In our spectroscopic analysis in § 2, we have therefore adopted this luminosity. The $T_{\text{eff}}$ derived from our spectral synthesis modeling is consistent with this scenario. These models are constrained by estimates of the properties of the preflash progenitor stars using their surrounding PNe (Kerber et al. 1999; Lechner & Kimeswenger 2004; Pollacco 1999).

### 3.3. Do R Coronae Borealis Stars evolve from FF Stars?

RCB stars are a rare class of H-deficient supergiants that undergo deep and random brightness declines due to dust, which forms near the stellar surface and then dissipates (Clayton 1996). The light-curve behavior and spectral appearance of V605 Aql in 1921 and the current light-curve behavior and abundances of Sakurai's object are reminiscent of the RCB class. There are, however, several reasons why FF stars are unlikely to be the evolutionary precursors of the majority of RCB stars.

The FF objects have shallower light declines (>10 mag) than do RCB stars (~8 mag). The abundances of FF objects, shortly after the outburst, do match those of RCB stars, except for one important difference: the presence of significant amounts of $^{13}$C in Sakurai's object, but not in RCB stars. In general, an RCB star will have $^{12}$C/$^{13}$C $\geq 100$ but in 1996, Sakurai's object had $1.5 \lesssim ^{12}$C/$^{13}$C $\lesssim 5$ (Pollard et al. 1994; Asplund et al. 1999). The high $^{13}$C might be a transient feature but measurements in near-IR spectra of Sakurai's object as late as 1998 June find a ratio of $^{13}$C/$^{12}$C $= 4 \pm 1$ (Eyres et al. 1998; Pavlenko et al. 2004). It is possible that the very low resolution 1921 spectrum of V605 Aql cannot resolve the $^{12}$C$^{13}$C $\lambda 4737$ bandhead from the $^{13}$C$^{13}$C $\lambda 4744$ band head and so the presence of $^{13}$C was not noticed (Clayton & De Marco 1997).

For a very short time, perhaps as short as 2 years, both V605 Aql and Sakurai's object were almost indistinguishable from the RCB stars in abundances, temperature, absolute luminosity, and light-curve behavior. The RCB-like spectrum (and presumably abundance pattern) of V605 Aql in 1921 was already very different in 1987 (Clayton & De Marco 1997). Unfortunately, this extremely short RCB phase of the FF stars means that they cannot account for even the small number of RCB
stars known in the Galaxy. There are about 50 RCB stars known, and it is predicted that there may be as many as ∼3000 in the Galaxy as a whole (Alcock et al. 2001; Zaniewski et al. 2005). From R CrB itself, we have a lower limit on the lifetime of an RCB star of ∼200 yr (Clayton 1996).

The abundances of V605 Aql in 2001 and Sakurai’s object in 1996 are listed in Table 1, along with the abundances of typical RCB and [WC] stars. If all FF stars behave like V605 Aql, their surface compositions will eventually make the transition from mostly helium to similar fractions of helium and carbon. This transition is likely to be due to mass loss, which progressively peels off the helium layer, uncovering the inter-shell region (Werner & Herwig 2006). These abundances (helium and carbon in similar amounts) are typical of the [WC] shell region (Werner & Herwig 2006). These abundances similarities imply that the FF could have produced the ∼60 [WC] central stars known today (Górny & Tylenda 2000). But then it is hard to explain why only A30 and A78 show the morphology of a FF object (large H-rich PN surrounding H-poor ejecta). The properties of V605 Aql today may show the very near future of Sakurai’s object. These stars provide a rare opportunity to view a stage of stellar evolution that proceeds on a timescale of months and years rather than centuries and millennia.

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| TABLE 1 |
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| **ABUNDANCES (%) by Mass** |
| **Star** | **H** | **He** | **C** | **O** |
| RCB* star | 0 | 98 | 1 | 0.2 |
| [WC]* star | 0 | 50 | 40 | 10 |
| Sakurai’s object | 0 | 90 | 7 | 3 |
| V605 Aql | 0 | 54 | 40 | 5 |

* Typical abundances for typical RCB stars and [WC] central stars of PNe (Asplund et al. 2000; De Marco & Barlow 2001).

** Abundances on 1996 October 7 (Asplund et al. 1999).