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High-resolution spectroscopy of QY Sge: an obscured RV Tauri variable?

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ABSTRACT

The first high-resolution optical spectra of QY Sge are presented and discussed. Menzies & Whitelock, on the basis of photometry and low-resolution spectra, suggested that this G0I supergiant was obscured by dust and seen only by scattered light from a circumstellar reflection nebula. The new spectra confirm and extend this picture. Photospheric lines are unusually broad indicating scattering of photons from dust in the stellar wind. The presence of very broad, Na D emission lines is confirmed. Sharp emission lines from low levels of abundant neutral metal atoms are reported for the first time. An abundance analysis of photospheric lines shows that the stellar atmosphere is of approximately solar composition but with highly condensable (e.g. Sc and Ti) elements depleted by factors of 5–10.

Key words: stars: individual: QY Sge – stars: variables: other.

1 INTRODUCTION

Our investigation of QY Sge (IRAS 20056+1834) was prompted by the report by Menzies & Whitelock (1988) on broad Na D emission lines in the spectrum of this G0 supergiant with a strong infrared excess. Broad Na D (and other) emission lines are seen in spectra of R Coronae Borealis stars taken at minimum light. Questions abound concerning the location of the broad-line emitting gas with respect to the R CrB star, and concerning the excitation mechanism for these lines. Insights into the formation of the broad lines may possibly be obtainable by observing other stars exhibiting similar lines; in particular, targets such as QY Sge where the emission lines seem to be a permanent feature of the spectrum. It was in this spirit that we observed QY Sge at high spectral resolution.

Menzies & Whitelock (1988) observed QY Sge at 3.5-Å resolution at several epochs in the late 1980s. The Na D lines were seen strongly in emission with a width of 140 km s^{-1} (FWHM) and at a velocity equal to the stellar absorption-line velocity to within the errors of measurement (±15 km s^{-1}). Other evidence for emission was offered: Ca II H and K showed emission cores, Ca I 4226 Å was weakly in emission and Hα was filled in by emission. Consideration of the absorption lines led to a spectral type of about G0I.

QY Sge's infrared excess signals the presence of a thick dust cloud for which Menzies & Whitelock estimated a blackbody temperature of about 600 K. Polarimetry at optical (Trammell, Dinerstein & Goodrich 1994) and infrared (Gledhill et al. 2001) wavelengths showed significant polarization with the degree of polarization increasing from the visual to a maximum of about 14 per cent in the J band and then decreasing to about 7 per cent in the H band and 3 per cent in the K band. Optical polarimetry provides an important clue to the location of the gas emitting the broad lines; the broad Na D emission lines are unpolarized, although the local continuum is polarized (Trammell et al. 1994). At about the H band and to longer wavelengths, the flux is principally emission from the dust, but at wavelengths shorter than H band, the flux is photospheric radiation scattered off the surrounding dust (Menzies & Whitelock 1988). The source has not been resolved spatially.

The parallels with the R CrB stars are several – yellow supergiant, dusty circumstellar cloud and broad emission lines – but incomplete in that QY Sge is not obviously H-deficient. The broad emission lines of R CrB stars are seen only after a star has faded by several magnitudes. Yet, QY Sge shows the broad lines at 'maximum' light. This happy circumstance arises because dust dims the star but not the region emitting the broad lines. While there may be similarities of geometry and excitation between QY Sge and the R CrB stars, their evolution is likely to have differed greatly. Menzies & Whitelock (1988) discussed several possible histories for QY Sge but were unable to decide whether the star was an evolved massive star or a low-mass post-AGB star. Others (Trammell et al. 1994; Gledhill et al. 2001) have assumed that QY Sge should be listed with post-AGB stars and protoplanetary nebulae.

2 OBSERVATIONS

QY Sge was observed with the McDonald Observatory 2.7-m Harlan J. Smith telescope and its '2dcoudé' cross-dispersed echelle spectrograph (Tull et al. 1995) on 1999 August 17 and 18, and 2000 June 14. The observed bandpass ran from about 3900 to 10 000 Å with gaps beyond about 5600 Å, where the echelle orders were

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incompletely captured on the Tektronix 2048 × 2048 CCD. An additional observation was obtained on 2001 July 13 using the Sandiford Cassegrain echelle spectrograph on the McDonald 2.1-m Otto Struve reflector (McCarthy et al. 1993). This spectrum recorded with a Reticon charge-coupled device (CCD) provided complete coverage of the interval 4500–5170 Å. Observations of a Th–Ar hollow cathode lamp provided the wavelength calibration. All spectra were obtained at a nominal spectral resolving power of 60 000. Data were reduced in the standard fashion using the IRAF[1] software package.

Spectra of γ Cyg, and 89 Her were also obtained with the '2dcoudé' spectrograph. Gamma Cyg is a normal F8Iab star. The spectrum of 89 Her, a warmer supergiant (spectral type F2Ib), includes sharp emission lines from low-excitation levels of abundant atoms, but lacks broad emission lines.

3 THE ABSORPTION- AND EMISSION-LINE SPECTRUM

Inspection of QY Sge spectra shows three obvious components: absorption lines representative of a late-F to early-G supergiant, sharp emission lines from resonance and low-excitation transitions of abundant neutral atoms, and a few broad emission lines (e.g. Na D and K I 7665 and 7699 Å lines).

3.1 The absorption lines

The absorption-line spectrum broadly resembles that of γ Cyg. A striking difference is that the lines of QY Sge are much broader. A few lines are clearly stronger in QY Sge than in γ Cyg. Among these are the C I lines (Fig. 1). Low-excitation lines of neutral metals are also stronger in QY Sge. A spectacular example is shown in Fig. 2: Fe I at 5060.1 Å from the resonance multiplet. This and similar lines are slightly redshifted relative to higher excitation lines (see below). A few lines are greatly weaker in QY Sge. These are lines of singly ionized atoms such as Sc II, Ti II, Y II and Nd II. Three examples are given in Fig. 2. Line weakening does not appear to be a result of overlying emission.

By inspection, the lines of γ Cyg are sharper than those in QY Sge. To facilitate a direct comparison of the spectra, we have broadened the spectrum of γ Cyg to match that of QY Sge. Assuming that a standard profile for a rigidly rotating star suffices, we find that a projected velocity $v \sin i = 30 \pm 5\,\mathrm{km\,s^{-1}}$ equalizes the linewidths in the two spectra. This exercise should not be taken to imply that rotational line broadening is necessarily responsible for the broader lines of QY Sge. The difference cannot be attributed to a higher microturbulence in the atmosphere of QY Sge (see below). Alternatively, if macroturbulence is invoked, the motions in QY Sge are highly supersonic, which is an improbable scenario. As we discuss below, the broadening is plausibly attributed to the receipt of photons not directly from the star but after scattering off moving dust grains in the stellar wind.

The radial velocity was measured from a set of unblended absorption lines. For the '2dcoudé' spectra about 150 lines were measured. Fewer lines (about 30) were selected from the Sandiford spectrum. The radial velocities are $-21 \pm 1.5\,\mathrm{km\,s^{-1}}$ for 1999 August 17 and 18, $-23 \pm 1.5\,\mathrm{km\,s^{-1}}$ for 2000 June 14, and $-9.1 \pm -2.2\,\mathrm{km\,s^{-1}}$ for 2001 July 13. The star is obviously a velocity variable, which is not surprising for such a luminous star. At this time, the systemic velocity is unknown.

Low-excitation Fe I and other lines show a more positive velocity by about 7–9 $\mathrm{km\,s^{-1}}$. While the equivalent widths of the higher excitation lines agree well with those of the lines in γ Cyg, the low-excitation lines with the more positive velocity are stronger in QY Sge than in γ Cyg. This difference rules out emission-line contamination of the low-excitation lines of QY Sge. These measurements refer to spectra taken in 1999 and 2000.

[1] IRAF is distributed by the National Optical Astronomical Observatories, which is operated by the Association for Universities for Research in Astronomy, Inc., under contract to the National Science Foundation.

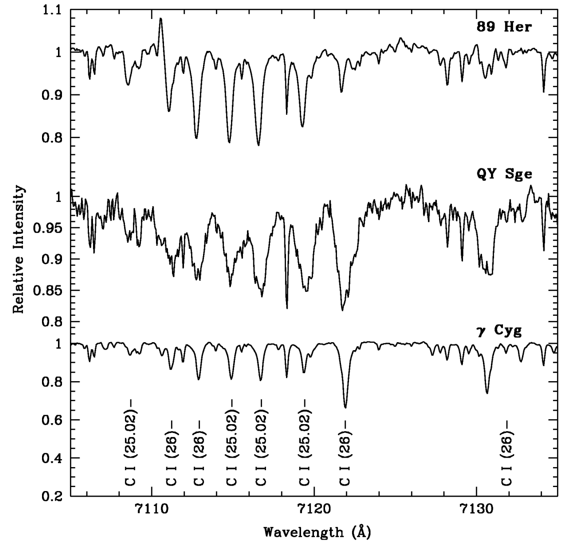

Figure 1. Spectra of 89 Her, QY Sge and γ Cyg from 7105 to 7135 Å. Lines of neutral carbon are prominent in this interval. Equivalent widths of C I lines are considerably larger in QY Sge than in γ Cyg.

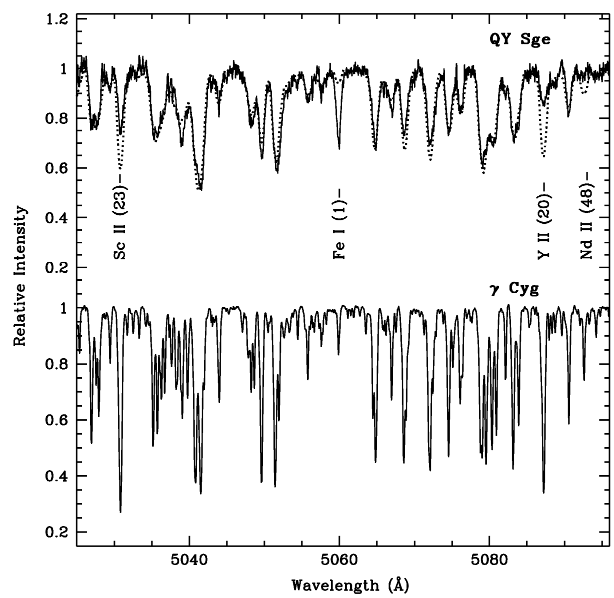

Figure 2. The spectrum of QY Sge (upper panel) from 5025 to 5095 Å with the spectrum of γ Cyg (lower panel). The dotted line in the upper panel is the spectrum of γ Cyg broadened by 30 $\mathrm{km\,s^{-1}}$ (see text). Many lines in the broadened spectrum match well the strengths of the same lines in QY Sge. Notable exceptions are the Fe I RMT1 resonance line, which is much stronger in QY Sge, and lines of Sc II, Y II and Nd II, which are weaker in QY Sge.

3.2 Sharp emission lines

The most prominent of the sharp emission lines are the Na D and K I resonance lines (Fig. 3). Weaker lines are scattered across the bandpass. These low-excitation lines are less common than in the spectrum of 89 Her, and also broader than their 89 Her counterparts. Among the weaker lines are the Fe I lines of multiplet RMT(12) of which an example is shown in Fig. 4.

The radial velocity of the emission peak for the strongest lines is $-21\,\mathrm{km\,s^{-1}}$ from the Na D lines, $-24\,\mathrm{km\,s^{-1}}$ from the K I lines, and $-24\,\mathrm{km\,s^{-1}}$ from the Ca II H line. These results are from the 1999 August spectrum, but the 2000 June spectrum gives similar results. The peak velocity is essentially equal to the absorption-line velocity given above. This may be a coincidence because it appears that these strong emission lines are flanked by absorption, a suspicion reinforced by the fact that the widths ($7\,\mathrm{km\,s^{-1}}$) of the emission lines are much smaller than those ($26\,\mathrm{km\,s^{-1}}$) of weaker lines.

The weak emission lines of Fe I [RMT(12) and RMT(13)] are at a velocity of about $-14\,\mathrm{km\,s^{-1}}$, which is the velocity of the absorption lines from the same low-excitation levels. and redshifted by about $7\,\mathrm{km\,s^{-1}}$ with respect to the absorption-line velocity measured from higher excitation lines. These emission lines are broad (FWHM $\simeq 26\,\mathrm{km\,s^{-1}}$) relative to their counterparts in 89 Her. The upper levels of the absorption lines of Fe I RMT(1) serve as the upper level of the emission lines from Fe I RMT(12). Similarly, the upper level for Fe I RMT(2) seen in absorption feeds Fe I RMT(13) seen in emission; iron atoms from low-lying states are absorbing photons and feeding them into other lines sharing the upper state. All of these measurements refer to the 1999 and 2000 spectra.

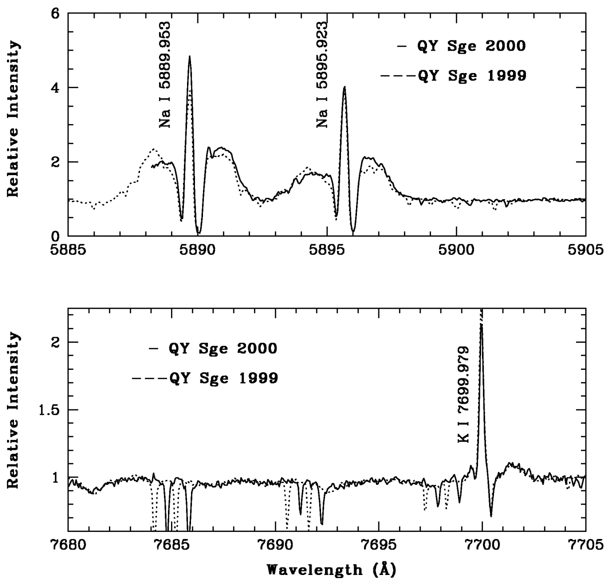

Figure 3. Spectra of QY Sge in 1999 August and 2000 June showing the emission profiles of the Na D lines (upper panel) and the K I resonance lines (lower panel). Note the presence of sharp and broad components for these resonance lines. The sharp absorption lines, especially prominent in the lower panel, are of telluric origin.

3.3 Broad emission lines

What drew us to study QY Sge was the report of broad emission lines. The most prominent are the Na D lines, which include a sharp line (Fig. 3). This figure also shows the K I resonance lines where the broad component is present but less prominent relative to the sharp emission component than in the Na D lines. Broad emission is weakly present in the Ca II H line. Fig. 5 compares the Na D profiles of QY Sge with profiles for three other stars: R CrB at minimum light, 89 Her and the normal supergiant γ Cyg. Gamma Cyg shows the photospheric Na D profile with two weak blueshifted absorption lines in the line cores; these are possibly interstellar components. For 89 Her, the photospheric Na D absorption lines appear partly filled in with emission, and complex blueshifted absorption present at about 2 Å from the deep absorption core is probably of circumstellar origin. Very weak

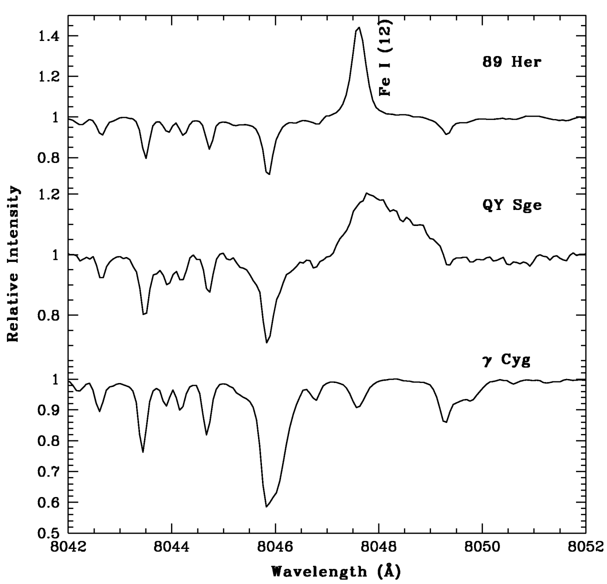

Figure 4. Spectra of 89 Her, QY Sge and γ Cyg from 7970 to 8060 Å. The prominent emission line of Fe I from RMT12 is seen in QY Sge and 89 Her.

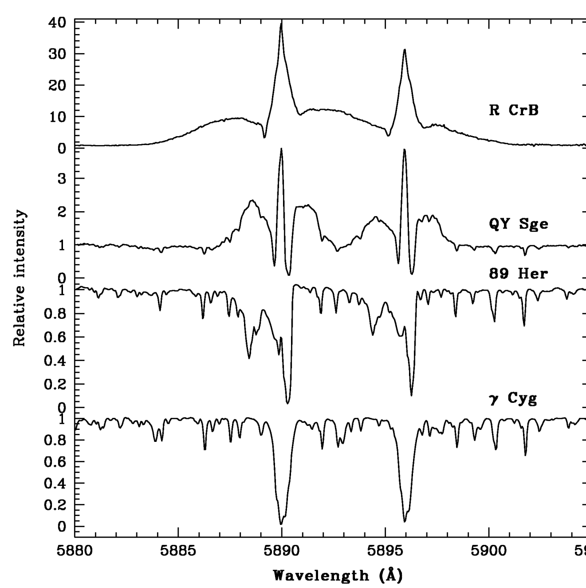

Figure 5. The Na D lines in R CrB at minimum light, QY Sge, 89 Her and γ Cyg. Some of the sharp absorption lines in these spectra are telluric H_2O lines.

emission may be present in the red wing of the D2 line. Broad emission in addition to sharp emission is seen in QY Sge and R CrB. For R CrB the broad emission of the red wing of D2 overlaps the blue wing of D1, but D1 and D2 are well resolved for QY Sge. The intrinsic profile of the broad lines in QY Sge is probably that of a single peak, but the superposition of the sharp emission and accompanying absorption creates the appearance of a broad emission split into a blue and red component of approximately equal intensity. Part of the central absorption may be contributed by the photospheric line. The D1/D2 flux ratio is slightly less than the value of 2 expected for optically thin lines.

The broad emissions of QY Sge are approximately centred on the stellar velocity. The average velocity of the blue and red peaks is $-24\,\mathrm{km\,s^{-1}}$ for the Ca II K line, and $-27\,\mathrm{km\,s^{-1}}$ for D2 and $-29\,\mathrm{km\,s^{-1}}$ for D1 from the 1999 August spectrum, for which the systemic velocity was $-21\,\mathrm{km\,s^{-1}}$. The separation of the blue and red peaks is about $130\,\mathrm{km\,s^{-1}}$. The base widths of the lines are about $270\,\mathrm{km\,s^{-1}}$. Emission in Hα may be related to these broad emissions: the P Cygni profile at Hα has red emission extending to $-100\,\mathrm{km\,s^{-1}}$ from the photospheric velocity.

4 AN ABUNDANCE ANALYSIS

Although it is recognized that the photosphere of QY Sge may have an unusual construction, it is useful to search for large abundance anomalies. Quite obviously, the low-excitation lines and lines contaminated by overlying emission should be excluded from the abundance analysis. In particular, we excluded resonance lines and lines that appear in emission in 89 Her. A standard local thermodynamic equilibrium (LTE) model atmosphere-based analysis was undertaken. Models were taken from Kurucz's grid (http://cfaku5.harvard.edu), and the current version of MOOG (Sneden 1973) was used to predict equivalent widths.

Usual procedures were used to determine the defining parameters: the effective temperature T_{eff}, the surface gravity $\log g$, the iron abundance [Fe/H] and the microturbulence ξ_t. A collection of unblended Fe I lines was used to determine T_{eff} and ξ_t. Then, a set of Fe II lines with the Fe I lines and the assumption of ionization equilibrium gave $\log g$. We obtained $T_{\mathrm{eff}} = 5850 \pm 200\,\mathrm{K}$, $\log g = 0.7 \pm 0.25$ in cgs units, $\xi_t = 4.5 \pm 0.5\,\mathrm{km\,s^{-1}}$ and $[\mathrm{Fe/H}] = -0.4 \pm 0.1$. These values are quite similar to those found for γ Cyg by Luck & Lambert (1981): $T_{\mathrm{eff}} = 6100\,\mathrm{K}$, $\log g = 0.5$, $\xi_t = 3.5\,\mathrm{km\,s^{-1}}$, and $[\mathrm{Fe/H}] = +0.1$, which is not a surprise given the similarity in the spectra of the two supergiants.

There is no evidence that QY Sge is hydrogen deficient. Paschen lines appear in QY Sge with strengths similar to those of the lines in γ Cyg. The Hα profile has a central absorption strength comparable to that of the photospheric line in γ Cyg. Furthermore, as noted below, the C I and CH lines return the same carbon abundance.

Derived abundances are given in Table 1 as $\log \epsilon(\mathrm{X})$ on the scale $\log \epsilon(\mathrm{H}) = 12$, [X/H] and [X/Fe]. The tabulated uncertainties are derived from the line-to-line scatter; the standard error is smaller by $\sqrt{N}$. Uncertainties arising from the errors in the model atmosphere parameters are less than about ± 0.2 dex. The fact that the absorption lines are broad introduces an above-average uncertainty in measurements of the equivalent widths.

Carbon and nitrogen are overabundant. The selection of C I and N I lines avoids very strong lines. As a check on our analysis, we analysed the C I lines in our spectrum of γ Cyg, obtaining the same abundance as Luck & Lambert (1981). There are CH lines in the spectrum of QY Sge. Analysis of these lines returned the carbon abundance in Table 1. The oxygen abundance is best determined from the [O I] lines; the 6363 Å line is present and useful despite mild contamination from the telluric emission line. The photosphere of the star is O-rich rather than C-rich. The overabundance of sodium is based on four low-excitation lines. The Na I lines are clearly stronger than in γ Cyg. This is also the case for the high-excitation S I lines.

For the underabundant elements (Sc, Ti, Y, Zr and Ce), the lines are obviously weaker than their counterparts in γ Cyg. The selected lines do not appear in emission in 89 Her, where emission lines are more numerous. It is striking that the heavy elements have unusual relative abundances: Y, Zr and Ce represented by weak lines are underabundant by about 1 dex, but Ba and Eu show approximately solar abundances. We explain this anomaly below. Although the Ba abundance is derived from the weakest of the observed lines, namely the 5853-Å line with an equivalent width of 288 mÅ, the Ba abundance is quite sensitive to the assumed microturbulence. The Y, Zr, Ce and Eu abundances are insensitive to the microturbulence.

These abundance anomalies are reminiscent of a pattern exhibited by the warmer RV Tauri variables, the photospheres of which are depleted in those elements that are the first to condense into grains as gas cools. Giridhar, Lambert & Gonzalez (2000), who discuss abundances derived for a sample of RV Tauri variables, show that the abundance anomalies are present only in the warmer stars. The T_{eff} and $\log g$ of QY Sge place it among the affected variables, as Fig. 6 shows. One may suppose that the report of photometric variations on a characteristic time-scale of 50 d (Menzies & Whitelock 1988) is a sign that QY Sge is a RV Tauri variable. The infrared excess of QY Sge is only slightly more extreme than that of the extreme case (AR Pup) included by Giridhar et al. in their discussion of infrared excesses: QY Sge has the infrared colours $J - K = 2.9$ and $K - L = 2.6$ (Menzies & Whitelock 1988), compared with $J - K = 2.6$ and $K - L = 2.1$

Table 1. Chemical composition of QY Sge.

Element	Z	$\log \epsilon$	N^a	$\log \epsilon_{\odot}{}^b$	[X/H]	[X/Fe]
C I	6	8.85 ± 0.26	9	8.52	+0.33	+0.59
N I	7	8.83 ± 0.15	4	7.92	+0.91	+1.15
O I	8	9.15	1	8.83	+0.32	+0.59
Na I	11	6.80 ± 0.21	4	6.33	+0.47	+0.73
Mg I	12	7.44 ± 0.28	2	7.58	−0.14	+0.12
Mg II	12	7.52	1	7.58	−0.06	+0.24
Al I	13	5.93	1	6.48	−0.55	−0.29
Si I	14	7.56 ± 0.20	10	7.55	+0.01	+0.27
S I	16	7.47 ± 0.10	3	7.26	+0.21	+0.47
Ca I	20	5.97 ± 0.14	11	6.36	−0.39	−0.13
Ca II	20	6.18 ± 0.06	2	6.36	−0.18	+0.08
Sc II	21	2.47 ± 0.22	5	3.13	−0.66	−0.40
Ti II	22	3.98 ± 0.04	3	4.98	−1.00	−0.74
Cr I	24	5.93 ± 0.25	4	5.68	+0.25	+0.51
Cr II	24	5.80 ± 0.20	7	5.68	+0.12	+0.38
Fe I	26	7.26 ± 0.22	76	7.50	−0.24	–
Fe II	26	7.22 ± 0.11	12	7.50	−0.28	–
Ni I	28	6.01 ± 0.12	8	6.25	−0.24	+0.02
Zn I	30	4.46	1	4.63	−0.17	+0.09
Y II	39	1.03 ± 0.12	4	2.24	−1.21	−0.95
Zr II	40	1.50	1	2.60	−1.10	−0.84
Ba II	56	2.07	1	2.17	−0.10	+0.16
Ce II	58	0.61	1	1.61	−1.00	−0.74
Eu II	63	0.34 ± 0.08	2	0.53	−0.19	+0.07

[a] Number of lines.
[b] Solar system abundance from Grevesse & Sauval (1998).

for AR Pup. Abundance anomalies are more severe for AR Pup than for QY Sge but Giridhar et al. note that these anomalies do not correlate well with the infrared excesses.

Abundance anomalies among the warm RV Tauri variables (Preston types RV B) are fairly well correlated with the condensation temperature ($T_{\rm cond}$) computed for equilibrium cooling of a solar composition gas at low pressure; the severest underabundances are found for those elements expected to condense out at the highest temperatures. The temperature $T_{\rm cond}$ is that at which 50 per cent of the element has condensed into solids. We take estimates of $T_{\rm cond}$ from Lodders & Fegley (1998) and Wasson (1985). For several elements, the former reference gives the temperature at which a compound starts forming. In such cases, we have referred to Wasson for the temperature at a pressure of 10^{-4} bar at which 50 per cent of the element is in solid compounds. Of course, the present atmosphere of QY Sge has a decidedly non-solar composition but a key influence on condensation of solids is where the C/O ratio is placed with respect to the critical value C/O = 1. QY Sge has and presumably has had a C/O ratio of less than 1, and, therefore, the assumption of a solar mix is likely to be a valid approximation. Fig. 7 shows [X/H] for QY Sge from Table 1 plotted against $T_{\rm cond}$. There is a clear tendency for the elements of highest $T_{\rm cond}$ to be underabundant relative to those of low $T_{\rm cond}$. Carbon and nitrogen should be discounted because they may have been altered during the course of the evolution of the star. Oxygen and sodium may also have been enriched. The initial metallicity of the star as indicated by sulphur and zinc is close to solar. It is notable that, in this case and unlike a majority of the RV B variables, iron and other elements are only slightly, if at all, depleted. The severe depletions are restricted to Sc, Ti and three heavy elements. The scatter at a fixed $T_{\rm cond}$ is similar to that for well-observed RV Tauri RV B variables. There is a reasonable correlation between the abundances [X/H] and the depletions measured for the cold interstellar diffuse clouds projected in front of ζ Oph. This is shown in Fig. 8 where the data for ζ Oph are taken from Savage & Sembach (1996). As noted above, nitrogen should be discounted because it may be enriched in QY Sge. Scandium and the heavy elements are not plotted for lack of estimates for ζ Oph. Aluminium probably falls on the general trend: our estimate is consistent with the result of Morton (1985) for ζ Oph of [X/H] of -3.1 to -3.4. For QY Sge, the heavy elements Y to Eu fit the trend with $T_{\rm cond}$ quite well: Ba and Eu with $T_{\rm cond} \simeq 1200$ K have approximately solar abundances but Y, Zr and Ce with higher $T_{\rm cond}$ are underabundant. There is no evidence from Fig. 7 that QY Sge is enriched in the *s*-process elements but this too is a common property of the RV Tauri variables.

Given the abundance anomalies, we suppose that, as in the

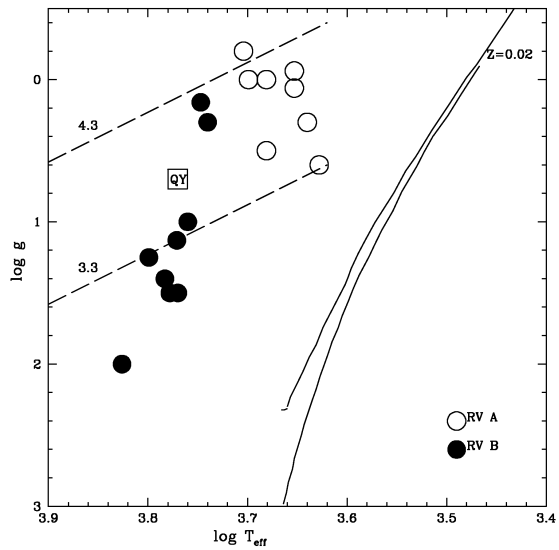

Figure 6. The log g versus log $T_{\rm eff}$ diagram for RV Tauri variables (Preston types RV A and B) and QY Sge. A theoretical isochrone (solid line) is shown for an age of 10^{10} yr and solar composition ($Z = 0.02$) from Bertelli et al. (1994): the red giant branch is represented by the rightmost solid line, and the AGB from the He-core burning stars to the most luminous AGB stars by the leftmost solid line. The dashed lines are tracks for a stellar mass of 0.8 $M_\odot$ evolving at a constant luminosity of log $L/L_\odot = 3.3$ (lower line) and 4.3 (upper line).

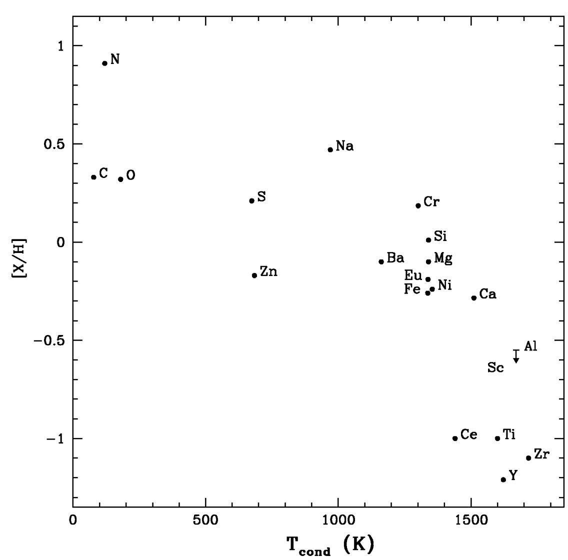

Figure 7. The abundance [X/H] versus the condensation temperature $T_{\rm cond}$. Elements are identified by their chemical symbols.

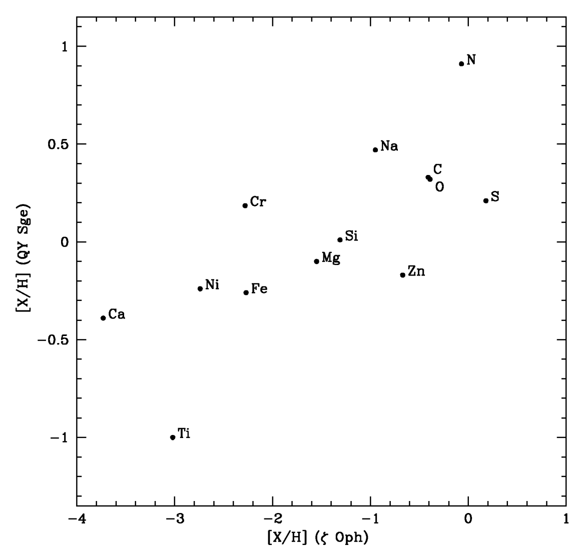

Figure 8. The abundance [X/H] for QY Sge versus [X/H] for the cold interstellar diffuse gas in front of ζ Oph. Elements are identified by their chemical symbols.

warmer RV Tauri variables, dust condenses in the environs of QY Sge and is expelled by radiation pressure. Not all the remaining gas is dragged away with the grains. Some of the gas is able to return to the star. If this winnowing of dust from gas is maintained for a long period, and, if mixing between the photosphere and the envelope is suppressed, the photosphere assumes the composition of the returning gas. QY Sge, which certainly now maintains a nearby reservoir of dust, appears to have a photosphere reduced in condensable elements. At the same time, the photosphere has approximately normal abundances of elements such as Si, Mg and Fe, which should be principal constituents of the circumstellar dust. From Fig. 7 we infer a dust temperature of about 1400 K for the regions of effective winnowing. This temperature is considerably hotter than the 600 K inferred from the infrared excess so that the effective regions are probably interior to the exterior of the thick dusty layers obscuring our direct view of the star.

5 THE CIRCUMSTELLAR ENVIRONMENT

Our observations provide several novel results to complement those presented by Menzies & Whitelock (1988) from low-resolution spectra and photometry. Their data led them to propose a model of ‘an extremely non-uniform circumstellar shell’ heated by starlight. In extending this idea, we must account for the characteristics of the three distinct spectroscopic components.

(i) The unusually broad photospheric absorption lines. The breadth is presumed to arise from Doppler shifts imposed by scattering off moving dust grains.

(ii) The sharp emission lines and the absorption lines of the pumping resonance lines. The fact that absorption and emission lines occur at the same radial velocity would suggest that the emitting and absorbing volumes are coincident and along the line of sight from the scattering surface to the observer.

(iii) The broad emission in the resonance lines of Na D, K I, Ca I and Ca II. Lack of polarization of the broad Na D emission lines implies that the emitted photons are not scattered from the surface contributing the photospheric spectrum. Trammell et al. (1994) in their polarization measurements did not resolve the Na D emission into its broad and sharp components, but we assume that because the lion’s share of the equivalent width was most probably contributed by the broad component that it is unpolarized; the sharp component may also be unpolarized. We also assume that the weaker broad lines are also unpolarized.

Adapting a geometry now recognized as not uncommon for the outer regions of post-AGB stars and planetary nebulae, we place the bulk of the dust in an equatorial torus with its inner edge close to the star, a requirement set by the derived blackbody dust temperature. Along the line of sight to the star, the dust is so optically thick that directly transmitted photospheric light contributes a negligible fraction to the observed optical spectrum. If the line of sight is inclined slightly to the plane of the torus, the rear of the inner edge of the torus will be visible but not the star (Fig. 9). In our picture, there is bipolar flow of gas from the star. It seems likely that the present wind from the 6000-K star contains little or no dust. The dusty torus may be leftover from the earlier life of the star as a mass-losing AGB star. There is evidence that even more evolved (i.e. hotter) post-AGB stars with strong infrared excesses are members of binary systems, for example, 89 Her (Walters et al. 1993) and HR 4049 (Bakker et al. 1998). The geometry recalls that proposed for VY CMa, a mass-losing M supergiant, by Herbig (1969, 1970).

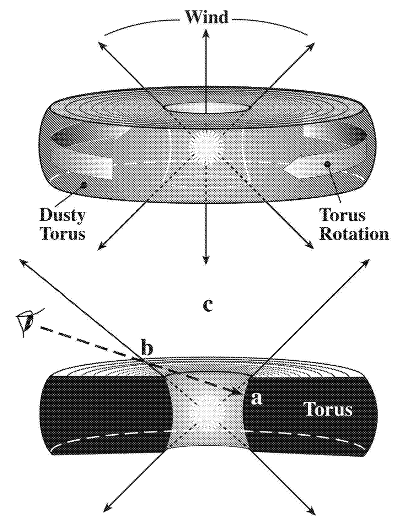

Figure 9. Sketch of a possible geometry for QY Sge and its circumstellar environment. Starlight reaches the observer after scattering off the inner edge (region *a*) of the dusty rotating torus. A bipolar wind off the star is the site for the formation of the sharp emission lines near the star (for example, the path-length *a* to *b*) and broad emission lines farther from the star (region *c*).

Qualitatively, the origins of the three distinct spectroscopic features may be placed as follows.

(i) The rear of the inner edge of the dusty torus is assumed to be primarily responsible for scattering the photospheric spectrum toward the observer. On the assumption that the dust is approximately in Keplerian motion, the line broadening will result from the Doppler shifts imposed by scattering over an extended part of the inner edge. The net Doppler shift should be close to zero.

(ii) Gas near the star between the observer and the inner edge of the torus is exposed to starlight. This gas should be at a low density such that most atoms and ions will be in their ground states. These atoms may be excited to give the sharp emission lines by photons received directly from the star or indirectly by photons scattered off the torus. Presumably the former are more numerous. In this case, the profile of the sharp emission line is set by the wind velocity (assumed to be radial), the opening angle of the bipolar flow and the angle of inclination of the torus to the line of sight. A resonance line seen in absorption in the spectrum of the scattered light from the inner edge of the torus will show the same spread in Doppler shifts as a sharp emission line. To within the measurement errors, the sharp emission and their exciting absorption lines do have the same width. Additional absorption in resonance lines may occur in the path between the star and the point of scattering off the torus. This absorption component will be Doppler-shifted to the blue relative to the scattered stellar light, and the accompanying emission, if visible to the observer, will be redshifted.

(iii) Broad resonance emission lines are assigned to resonance fluorescence by stellar photons interacting with atoms in the bipolar flow. If the torus is of large radius, the emission from the receding half of the bipolar flow will be occulted, and the observed emission line will show a small net blueshift with a magnitude dependent on the wind velocity, and the tilt between the axis of the bipolar flow and the line of sight. According to Fig. 9, the width of the emission line will depend on the same factors; emitting gas far from the torus will have line-of-sight velocities from approximately

$-v_{\rm w}^{\rm g}\cos\theta$ to $+v_{\rm w}^{\rm g}\cos\theta$, where $v_{\rm w}^{\rm g}$ is the velocity of the gas at that radial distance from the star and 2θ is the angle subtended at the star by the inner edge of the torus. The observed linewidth implies a wind velocity of about 100–150 km s^{-1}. Since the torus is considered here to be the polarizing source for the scattered photospheric spectrum, the Na D and other broad emission lines will be polarized differently and probably to a significantly smaller degree.

The model makes qualitative predictions concerning velocity shifts relative to the systemic stellar velocity. At this time, too few observations of the stellar absorption lines are available to determine the systemic velocity. Measured velocities are also affected by possible changes in the net velocity imposed by the scattering surface. It should be noted that the model does not explain readily why the emission lines are either sharp or broad. This is particularly an issue for the broad lines that are obviously accompanied by a sharp line (Fig. 3). Our model supposes both lines are formed in the bipolar flow. It seems necessary to invoke a sharp transition from a low- to a high-velocity wind but this should occur without a large change in physical conditions of the gas; the sharp lines are formed below the transition point and the broad lines above.

6 CONCLUDING REMARKS

QY Sge is identified here as being descended from a luminous red giant on either the higher reaches of the red giant branch (RGB) prior to helium ignition or the AGB. Assuming a mass of about 1 M$_\odot$, QY Sge's $T_{\rm eff}$ and $\log g$ correspond to a luminosity $L \simeq 10^4$ L$_\odot$. This is achieved by a star near the tip of the RGB or quite advanced along the AGB (Fig. 6). Carbon enrichment of the surface following the expected depletion resulting from the first dredge-up early on the RGB could possibly have occurred during the He-core flash at the tip of the RGB but more likely is a result of the third dredge-up early on the AGB; the star evolved away from the AGB before the *s*-process manufactured heavy elements in large quantities in the He-shell.

QY Sge is probably quite distant from the Sun. Menzies & Whitelock used the apparent bolometric magnitude from the flux curve in combination with assumed absolute bolometric magnitudes to arrive at a distance. For example, adopting their $m_{\rm bol} \sim 8.5$ and including a small bolometric correction, our luminosity estimate puts the distance to QY Sge at about 3 kpc. This is an upper limit because the dust cannot block all of the stellar radiation, and, furthermore, the optical fluxes depend on the efficiency of the scattering of light by the less dusty regions. Interstellar absorption is small. Menzies & Whitelock estimated $A_V \sim 1.2$ mag from the $B-V$ and the intrinsic colours of a G0I star, and noted that reddening maps suggest $A_V \sim 2$ for distances greater than about 600 pc. An independent estimate of reddening is possible from our detection of the diffuse interstellar band at 6284 Å. The equivalent width of the band of 461 mÅ with a calibration offered by Somerville (1995) gives $E(B-V) \simeq 0.40$, or $A_V \simeq 1.2$. Circumstellar absorption for the direct light from the star is substantial; we estimate about 6 mag for the visual band from comparison of the infrared (I, J, H) colours with the colours of unreddened G supergiants.

QY Sge, as noted above, shares $T_{\rm eff}$, $\log g$ and abundance anomalies with the RV Tauri variables. This association suggests that stars may commonly depart the AGB because of severe mass loss and that QY Sge is not the result of freak circumstances. A link with the RV Tauri variables recalls the suggestion that all RV Tauri variables belong to binary systems with substantial circumbinary dusty discs (Van Winckel et al. 1999). In addition, QY Sge has many similarities with 89 Her, a spectroscopic binary with a very low-mass companion to the post-AGB primary: similar Hα profiles, similar sharp low-excitation emission lines of neutral metals, and a considerable infrared excess (Walters et al. 1993). There is one prominent difference between the pair: 89 Her shows a blueshifted high-velocity absorption at Na D in place of QY Sge's broad emission lines, but, according to our model, QY Sge would show such absorption if seen pole-on.

Further photometric and spectroscopic observations are desirable to investigate whether QY Sge is a RV Tauri variable and/or a spectroscopic binary. At present, we cannot guess the systemic velocity. Higher-quality spectra would be useful in order to effect line profile comparisons of emission and absorption lines for the low-excitation transitions. Inflow of gas on to the star may be occurring in order to sustain the abundance anomalies (Fig. 7). Is gas from the inner edge of the torus falling on to the star? If so, high-resolution high signal-to-noise ratio spectra around key resonance lines may reveal the infalling gas in the spectrum of the light scattered off the inner edge of the torus. This would be the first detection of such a gas stream in stars affected by a winnowing of gas from dust.

Our attention was drawn to QY Sge by the report of broad Na D emission lines. Very few stars show such lines in their spectra. Apart from the R CrB stars observed in deep minimum, QY Sge may have very few cousins; we noted VY CMa and Lloyd Evans (1997) mentions IRAS 13258–8103 as having strong Na D emission. The geometry of the circumstellar material suggested for QY Sge may be a common one. Menzies & Whitelock point out that, if viewed from another angle, QY Sge would be observed as a normal supergiant with a relatively weak infrared excess. 'Perspective effects' give QY Sge its prominent infrared excess and strong broad emission lines. This geometry would in principle account for the lines in the R CrB stars, but they also show high-excitation He I (and other) lines.

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