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Research Note

On the nature of AFGL 2477*

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Abstract. Because of its bimodal spectral energy distribution and featureless LRS spectrum, AFGL 2477 has been suggested to be a carbon-rich post-AGB star. In this paper we argue against this hypothesis (based on our finding that the alleged optical counterpart is *oxygen*-rich) and propose that there are two stars close together on the sky (within 5″ of each other) which probably are not physically related. A more exotic scenario is also discussed.

Key words: binaries: general – circumstellar matter – stars: individual: AFGL 2477 – stars: mass loss – stars: AGB, post-AGB

1. Introduction

AFGL 2477 (= IRAS 19548+3035; $l = 67.^{\circ}4$, $b = 1.^{\circ}02$) is a bright red IRAS source (S_{12} = 75.1 Jy, S_{25} = 109 Jy) that has attracted attention ever since its discovery in the AFGL-survey. Gosnell et al. (1979) and Hrivnak et al. (1985) presented finding charts of the (alleged) optical counterpart to the IRAS source. Kwok et al. (1987) presented infrared photometry and hypothesized that, because of the lack of a silicate feature, it is a carbon star or an oxygen-rich star where the silicate feature is just in the transition from emission to absorption.

Volk et al. (1992) presented optical photometry of the counterpart suggested by Hrivnak et al. (1985) and found that the spectral energy distribution (SED) is bi-modal, and proposed that AFGL 2477 is a post-AGB star as many (suggested) post-AGB candidates have a double peaked energy distribution: a local maximum in the optical region due to the central post-AGB star, and a peak in the infrared due to a detached remnant AGB shell (see e.g. Slijkhuis 1992; Oudmaijer et al. 1992).

Because of its possible carbon star character, AFGL 2477 was included as a target in a program to search for the 3.1 μm feature; a well-known feature in carbon stars which is due to HCN and C_2H_2 (Ridgway et al. 1978). These observations were reported on in Groenewegen et al. 1994 (hereafter GJG94). Interestingly, the 3.1 μm feature was not detected in AFGL 2477. Moreover, the 2-4 μm spectrum showed an upturn near 3 μm (see also Fig. 1) providing evidence for either a detached shell around the central star, or for two stars located within the aperture, both contributing to the light in the 2-4 μm region.

In this paper B, V and I photometry and an optical spectrum of the possible optical counterpart to AFGL 2477 are presented. The spectral energy distribution over the range 0.5 to 100 μm is constructed and fitted with a dust radiative transfer model. We discuss the possible nature of AFGL 2477 based on the model results, the new and existing observational data.

2. Observations

In Fig. 1 we present the 2.2-3.8 μm observations of AFGL 2477, taken from GJG94. The spectrum was obtained on September 7, 1990 with the CGS2 instrument on the UKIRT. The aperture was 5″ and the spectral resolution ($\lambda/\Delta\lambda$) was 350 at 3.1 μm (see GJG94).

Several band heads of ^{12}CO can be identified between 2.29 and 2.45 μm. Closer inspection reveals no trace of the ^{13}CO band heads (see Sect. 3.1). The presence of CO indicates an effective temperature of the star of less than about 7500 K. There is no obvious 3.1 μm feature present in the spectrum.

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* Based on observations obtained with the WHT and JKT operated on the island of La Palma by the Royal Greenwich Observatory in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias.

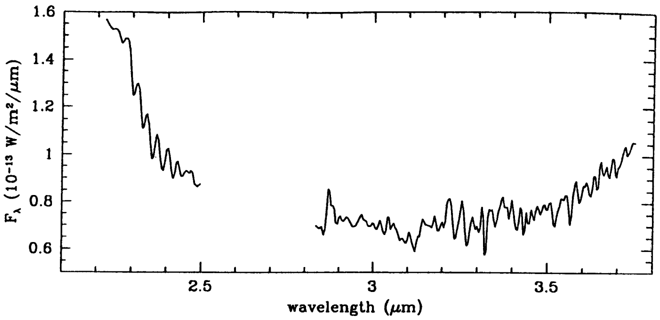

Fig. 1. The 2-4 μm spectrum taken from GJG94.The typical noise level is 1% short ward of 2.5 μm and about 5% long ward of 2.9 μm. The atmosphere is not transparent between 2.5 and 2.8 μm

In the following section we discuss new and existing observational data on AFGL 2477. Based on Fig. 1 it seems natural to divide the discussion into two parts, based on whether the wavelength is shorter or longer than 3 μm.

2.1. The light emitted short ward of 3 μm

2.1.1. Astrometry

The coordinates listed in the literature for AFGL 2477 are as follows: the IRAS PSC gives R.A. = $19^h54^m48.8^s$, Dec = $30°35'53''$ (epoch 1950) with an error ellipse of $20''$ x $5''$ and a position angle of 72°; Joyce et al. (1977) list 49.2^s, $54''$ with an uncertainty of $5''$ and Gosnell et al. (1979) quote 50.0^s, $57''$ with an uncertainty of $10''$ in each coordinate.

To identify the possible optical counterpart of the IRAS source, we inspected digitized versions of the Palomar E and O plates, which were kindly provided by Dr. Mike Irwin (RGO). Combining the quoted positions and their uncertainties, there is only one suitable counterpart, visible on both the E and O plate, located at R.A. = $19^h54^m49.36^s$, Dec = $30°35'57.4''$ (epoch 1950). If the observed 2-4 μm spectrum is due to two stars in the aperture, then we can only say that the counterpart of the IRAS source is located within $5''$ of this position.

2.1.2. Optical photometry

On April 11 and 12, 1992 we obtained B, V, and I images in the Cousins system of the field near the IRAS position using the 1.0-m Jacobus Kapteyn Telescope (JKT) on La Palma. The detector was the GEC#3 CCD of 385 × 578 pixels.

In Fig. 2 part of the V and I CCD images are presented as finding charts. The counterpart suggested in the previous subsection is indicated. This candidate agrees with that previously identified by Hrivnak et al. (1985).

The photometry of this star is $B = 17.1$, $V = 14.8$ and $I = 12.2$ magnitudes. The error is about 0.1 in all three bands. The $(B - V)$ color is in good agreement with that estimated from the Palomar E and O plates.

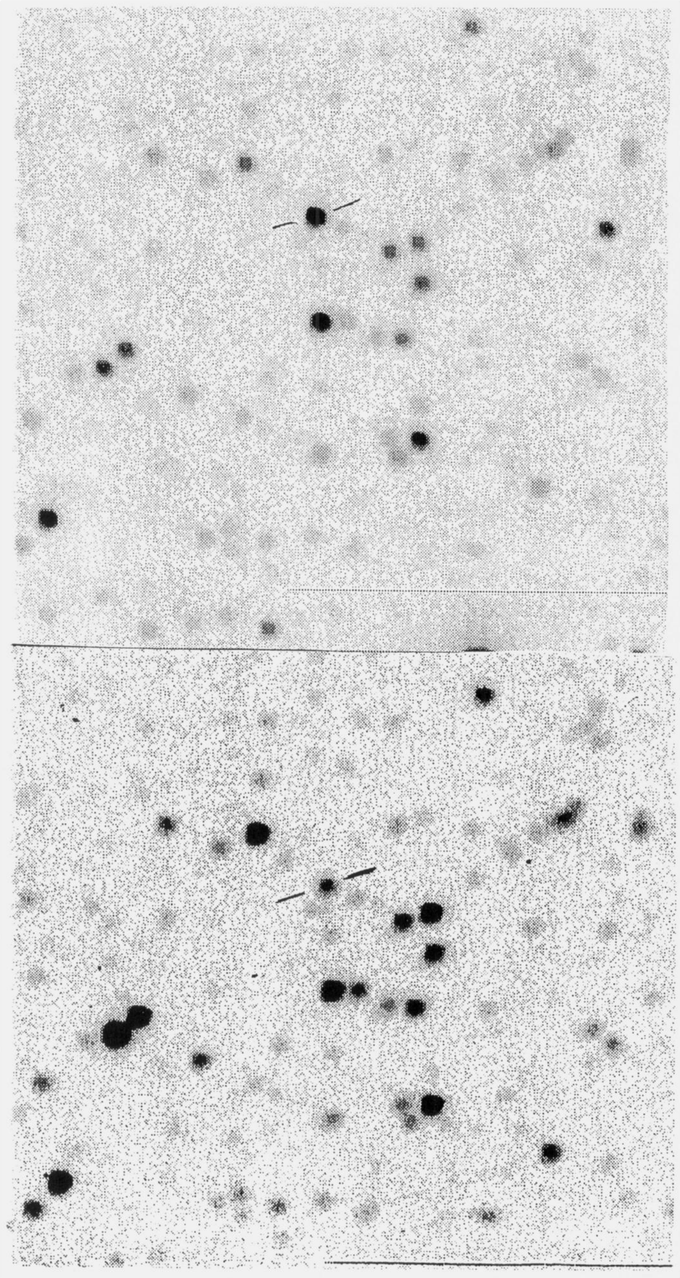

Fig. 2. Finding chart of AFGL 2477 in the V (upper panel) and I band. The size is approximately $2' \times 2'$ with North to the top and East to the right

2.1.3. Optical spectroscopy

We obtained optical spectra for the star indicated on the finding charts in the ranges 4600 – 5400 Å and 6200 – 7100 Å on May 26, 1992, using the 4.2-m William Herschel Telescope on La Palma. We used the ISIS double spectrograph with gratings R600B and R600R. The detectors were EEV #2 and EEV #3 which have 1242 × 1152 pixels. The slit width was $1''.2$, yielding a resolution (FWHM) of 1.9 Å. Wavelength calibration was performed using a helium-argon lamp for the blue spectrum, and a neon lamp for the red spectrum.

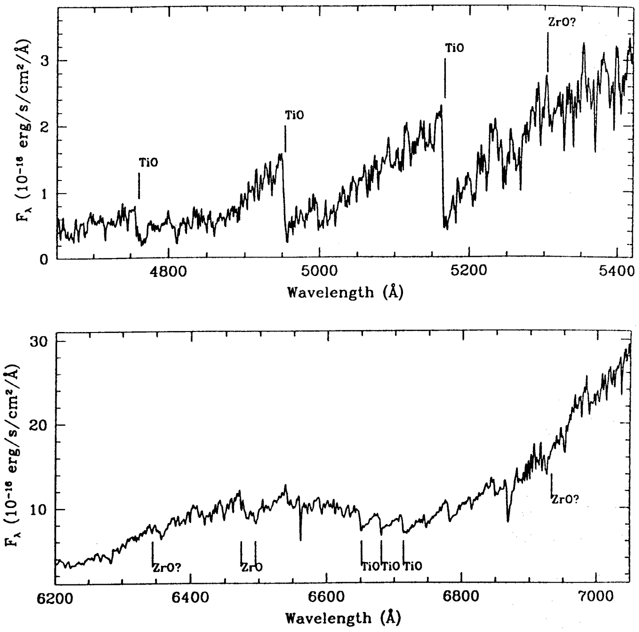

Fig. 3. The observed optical spectrum of AFGL 2477

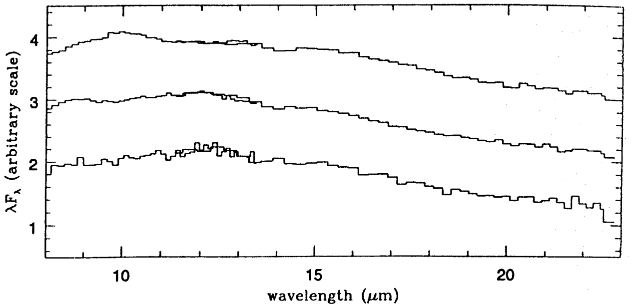

Fig. 4. The LRS spectra of AFGL 3068 (top), AFGL 5625 (middle) and AFGL 2477 (bottom). The LRS spectra of AFGL 3068 and 5625 were first scaled to that of AFGL 2477 at 23 μm and then off-setted by 2 and 1 y-scale unit, respectively

The observed spectrum is shown in Fig. 3. The TiO band heads at 4761, 4954, 5167, 6652, 6681 and 6714 Å are readily identified. In addition, weak ZrO band heads are identified at 6474 and 6495 Å, and possibly also at 5304, 6345 and 6933 Å. We compared the spectrum to the spectra of M-giants from Fluks et al. (1994) and the spectra of M-giants and dwarfs in Turnshek et al. (1985). Based on the line ratios of the TiO bands and the weak presence of ZrO we classify the spectrum as M6S III (or S6/1 III) with an uncertainty of 1 subclass. The presence of the s-process element zirconium indicates an evolved nature of the star.

Based on a comparison of the observed $B-V$ and $V-I$ colors to the theoretical extinction-free colors of an M6 giant (Schmidt-Kaler 1982; Fluks et al. 1994) we infer a total (circumstellar plus interstellar) extinction of A_V = 2.1-2.4 magnitudes towards AFGL 2477.

2.2. *The light emitted long ward of 3 μm*

2.2.1. The LRS spectrum

In Fig. 4 we compare the LRS spectrum of AFGL 2477, to that of two known carbon stars with very red colors. Both AFGL 3068 and AFGL 5625 show the 3.1 μm feature (Jones et al. 1978, GJG94) and therefore are genuine carbon stars. The LRS spectrum of AFGL 2477 is strikingly similar suggesting that it may also be a carbon star. Examples of extremely red (possible) carbon stars with near featureless LRS spectra are further discussed in Groenewegen et al. (1992), Volk et al. (1992) and Omont et al. (1993).

2.2.2. Molecular data

In this section we discuss the literature data on molecular emission lines. The star has been detected in ^{12}CO J = 1-0 and 2-1 and HCN J=0-1 (Zuckerman & Dyck 1989; Likkel et al. 1991; Omont et al. 1993).

Recently, Bujarrabal et al. (1994) presented criteria to separate oxygen-rich from carbon-rich stars based on the ratio of integrated intensities of several molecules. One of their criteria is based on the ratio of ^{12}CO(1-0)/HCN(1-0). The published ^{12}CO(1-0) spectrum (Likkel et al. 1991) is noisy and they quote an expansion velocity much larger than that derived from the higher signal-to-noise ^{12}CO(2-1) and HCN(1-0) spectra presented by Omont et al. (1993). We estimate the integrated intensity of the ^{12}CO(1-0) profile between $V_{\rm LSR}$ –20 and +30 km s^{-1} (the extension of the profiles in the high signal-to-noise spectra) as 17.5 K km s^{-1}, and put a firm upper limit of 20 K km s^{-1}. Since both the CO and HCN lines were measured with the same telescope no further corrections are necessary and we find a ^{12}CO(1-0)/HCN(1-0) ratio of 0.33. The ratio which discriminates oxygen-rich from carbon-rich sources is 0.18 (Bujarrabal et al. 1994; excluding supergiants) carbon stars having ratios above this value. This strongly suggests that the region where the CO and HCN emission arises is carbon-rich.

This is further supported by the observations of OH and H_2O. AFGL 2477 has no 22 GHz water maser (Lewis & Engels 1993) and has repeatedly not been detected in either 1612, 1665 or 1667 MHz OH maser lines, including twice in the sensitive Arecibo survey (Silverglate et al. 1979; Lewis et al. 1987; Likkel 1989; Lewis 1992). AFGL 2477 has a [25 – 12] color of –0.245 (using the definition in Lewis 1992) and has a high probability of being variable; the IRAS VAR index is 99. The detection probability of OH in the Arecibo survey for stars with similar [25 – 12] colors and VAR $\geq$ 90 is 75.2%.

The presently available molecular data strongly support a carbon-rich nature for the circumstellar shell of AFGL 2477.

3. Fitting the spectral energy distribution

Considering the possibility mentioned in the Introduction that the observed SED may be due to two different stars, we have fitted the optical and the near- and far-infrared SED separately

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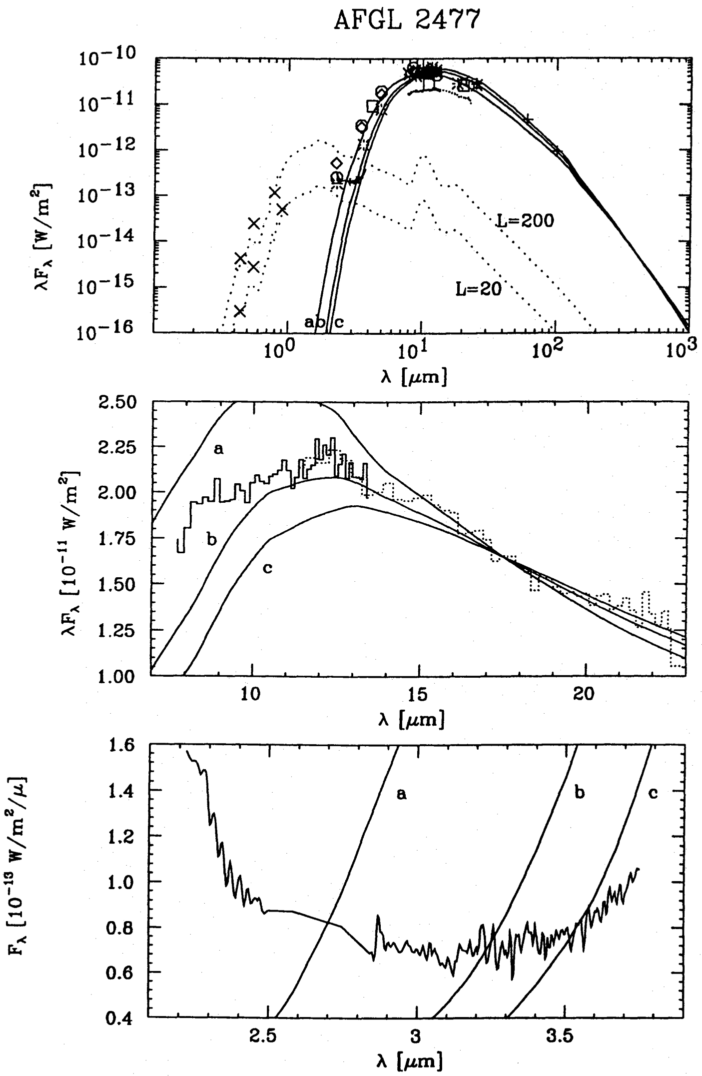

Fig. 5. The model results of fitting the optical and near- and far-infrared data of AFGL 2477 separately. In the top panel the SED is shown. The solid lines represent the models of the carbon star with a carbon-rich CSE. The letters *a*, *b*, *c* represent models with mass loss rates of 1.0 10^{-4}, 1.6 10^{-4} and 2.0 10^{-4} $M_\odot$/yr respectively, with a temperature at the inner dust radius of 900 K. The dotted lines represent the models of the M-star with an oxygen-rich CSE, with the luminosity of the M-star indicated (assuming d = 1.6 kpc). In the middle panel the LRS spectrum is shown together with the models of the C-star with a carbon-rich CSE. The models have been scaled to the observations at 17.5 μm. In the bottom panel the 2-4 μm spectrum is shown together with the models of the C-star with a carbon-rich CSE. The following symbols for the photometry are used: + = IRAS, X = *B*, *V*, *I*-photometry (this paper and Volk et al. 1992), ◇ = Ney & Merrill (1980), □ = Price & Murdock (1983), ∗ = Lawrence et al. (1990), O = Gosnell et al. (1979), □ = Kwok et al. (1987). The IRAS fluxes are multiplied by a factor of 2.4 to let them agree with the other photometry near 12 μm

Table 1. Parameters of the radiative transfer models

L ($L_\odot$)	$\dot{M}$ ($M_\odot$/yr)	T_c (K)	d (kpc)	$r_{\rm inner}$ (R_*)	$\tau_{0.5}$
C-star + carbon-rich shell					
7050	1.0 (-4)	900	1.73	10.5	49.5
7050	1.6 (-4)	900	1.66	11.4	72.7
7050	2.0 (-4)	900	1.61	11.9	83.1
M-star + oxygen-rich shell					
20	4.7 (-8)	1000	1.60	8.25	0.90
200	1.5 (-7)	1000	1.60	8.25	0.90

Listed are the luminosity of the central star, the mass loss rate ($a\,(-b)$ stands for $a\ 10^{-b}$), the temperature of the dust at the inner dust radius, the distance, the inner radius and the dust optical depth at 0.5 μm. The value of the mass loss rates is based on a grain specific density of 2.0 gr cm^{-3} and a dust-to-gas ratio of 0.005.

using a radiative transfer model. We assume an oxygen-rich M-star dominant in the optical light and a carbon star dominating the near- and far-infrared part of the SED. If these stars form a physical binary system, the ratio of the luminosities of the individual components should be consistent with models for stellar evolution.

The SED is modeled using the dust radiative transfer model of Groenewegen (1993). This model simultaneously solves the radiative transfer and the radiative equilibrium equation for the dust in spherical geometry. The calculations are done in the small particle limit.

For the fit to the near- and far-infrared data we use a central star represented by a blackbody with a typical carbon-star effective temperature of 2500 K surrounded by a carbon-rich CSE. For carbon-rich dust, the absorption coefficients of amorphous carbon are used (Rouleau & Martin 1991), since the LRS spectrum indicates there is little, if any, silicon carbide present. For $\lambda > 30$ μm we adopt $Q_\lambda \sim \lambda^{-\beta}$ and determine β by fitting the observed IRAS 60 and 100 μm flux-densities (we find β =1.2-1.5). The expansion velocity of the circumstellar shell is v = 23.0 km s^{-1} (derived from the molecular data, see Sect. 2.2.2). The velocity is assumed to be constant with radius. The model parameters are: the (arbitrary) luminosity L, the distance d, the temperature of the dust at the inner radius T_c and the constant mass loss rate $\dot{M}$.

The theoretical SEDs have been corrected for interstellar extinction. Neckel & Klare (1980) find that in a field in the direction $l = 66°$, $b = 1°$ the extinction is about $A_V = 1.2$ for distances between 0.8 and 2.5 kpc and about $A_V = 2.1$ for distances between 2.5 and 5.5 kpc. We have assumed $A_V = 1.2$ in the calculations below, since for an AGB luminosity of 7050 $L_\odot$ the distance is about 1.6 kpc. The results are not sensitive to the adopted extinction and do not change any of the conclusions. To calculate the extinction at other wavelengths we use Cardelli et al. (1989).

For the fit to the optical data we use the flux of an M6 giant (from Fluks et al. 1994; effective temperature is 3295 K), surrounded by an oxygen-rich CSE consisting of silicate dust. For the silicate dust opacity we adopt the combination of Jones & Merrill (1976) for $\lambda < 8$ μm and by David & Papoular (1990) for $\lambda > 8$ μm, smoothly joined at 8 μm. We assume a typical dust condensation temperature of 1000 K and a typical expansion velocity of the oxygen-rich CSE of 15 km s^{-1}.

The luminosity of the carbon-star is arbitrarily assumed to be 7050 L$_\odot$; the luminosity of the M-star is calculated for an assumed distance of 1.6 kpc.

For the carbon star we present in Fig. 5 (see model parameters in Table 1) three models with T_c = 900 K. The results are insensitive to the exact choice of T_c. The different mass loss rates have been chosen as to fit the SED (model a), the LRS spectrum (model b) and the upturn in the spectrum near 3.5 μm (model c).

For the fit to the optical photometry we have used an additional constraint since the circumstellar extinction is expected to be in the range 0.9-1.2 magnitudes (2.1-2.4 magnitudes total extinction derived from the colors of the M6 star minus ~1.2 magnitudes interstellar extinction) if the C-star and the M-star are at the same distance. The models shown in Table 1 and Fig. 5 have been calculated for A_V = 0.9 magnitudes. Models with A_V = 1.2 magnitudes would require mass loss rates which are larger by a factor of 1.33 than those quoted in Table 2 and would result in slightly redder spectra.

Since both stars are variable it is difficult to estimate the ratio of the luminosities of the carbon-star to that of the M-star. For assumed equal distances of the M-star and the C-star, a luminosity of 60 L$_\odot$ is required for the M-star to fit the observed 2-4 μm spectrum (Fig. 5). We derive a ratio of the luminosities (denoted R) of R = 120 (= 7050/60). The estimated range in R is between 15 and 350 based on the range of 20-200 L$_\odot$ in the luminosity of the M-star and the possibility that the C-star may be a factor of 2.4 less luminous at its photometric minimum.

4. The nature of AFGL 2477; single, binary or coincidence in the sky?

Based on the results of our new observations and model fitting in the previous section, and the data reported in the literature the object AFGL 2477 can be interpreted in four different ways. A single object consisting of (a) an oxygen-rich star surrounded by an oxygen-rich circumstellar shell, or (b) an oxygen-rich star surrounded by an carbon-rich circumstellar shell. Alternatively, there are two stars involved with (c) a binary consisting of a oxygen-rich star and an (obscured) carbon star, or (d) a coincidence in the sky of an oxygen-rich star and an (obscured) carbon star. We will discuss these alternative scenarios below

4.1. Single star scenario

We first consider an an oxygen-rich star surrounded by an oxygen-rich circumstellar shell. The reason to consider it is that a featureless LRS spectrum as observed for AFGL 2477 (see Fig. 4) leaves open the possibility that the silicate feature is just in the transition from emission into absorption (as suggested for this object by Kwok et al. 1987). We have modeled the full SED of AFGL2477 using silicate grains and an M6 central star (see details in the previous section) and find that the silicate feature is deeply in absorption ($\tau_{9.9\mu m} \approx 20$). This model can therefore be ruled out. The shape of the LRS spectrum and the molecular data indicate beyond doubt that the circumstellar shell is carbon-rich.

We now consider an oxygen-rich star surrounded by an carbon-rich circumstellar shell.

We have tried to fit the full SED using a carbon-rich shell around a central M6 star. None of the models fitted the observed SED, the problem being the balance between the luminosity emitted in the optical and the infrared region. The SED may possibly be fitted with a non-spherically symmetric dust shell. In this case a pole-on geometry has to be invoked since we found that models that fitted the infrared data best, predicted too low fluxes in the optical.

One can ask the general question whether a carbon-rich shell around an oxygen-rich star is expected at all. In the course of the evolution of intermediate mass stars, oxygen-rich stars may become carbon stars. This is related to the dredge-up of carbon after a thermal pulse (see e.g. the review of Iben & Renzini 1983). Since the transition from an oxygen-rich to a carbon star occurs on a mixing time scale which is much shorter than the flow time scale of the circumstellar envelope (CSE), it is possible to see carbon stars with an oxygen-rich CSE. This is in fact one of the possible explanations for the few carbon stars which display the silicate feature in their LRS spectra (Willems & de Jong 1986; Little-Marenin 1986). Possibly a star could change back from a carbon star to an M-star due to a process called hot-bottom burning (HBB), that is the burning of carbon to nitrogen at the base of the convective envelope. It has been inferred both observationally (Plez et al. 1993 and references therein) and theoretically (e.g. Boothroyd et al. 1993) that HBB occurs in certain stars. It is unclear however if a star can actually follow the path M→C→M. In the few available theoretical models, HBB prevents the formation of carbon stars above a certain luminosity, i.e. stars remain oxygen-rich (e.g. Boothroyd et al. 1993). Stars at the boundary where the formation of carbon stars is prevented, are predicted to have an initial mass $\gtrsim 5$ M$_\odot$, be luminous ($M_{\rm bol} \approx -6.4$), show the sign of the s-process (i.e. be MS or S stars), have a low ^{12}C/^{13}C ratio (4 - $\lesssim$10) and be rich in lithium.

Regarding the ^{12}C/^{13}C ratio we noted earlier that no clear ^{13}CO band heads are visible near 2.3 μm, suggesting that the ^{12}C/^{13}C ratio is not low. However, we are unable to quantify this.

With a luminosity of 28000 L$_\odot$ ($M_{\rm bol}$= –6.4) the system would be at 3.2 kpc, and the distance to the galactic plane 55 pc. This is consistent with a massive progenitor.

The star has a spectral type MS in accordance with the expectation.

On the other hand, there is no lithium line present at 6708 Å in the spectrum of AFGL 2477. We compared the spectrum with that of lithium rich stars (Plez et al. 1993 and Abia et al. 1991). These spectra were obtained with a higher resolution of 20000 but the lithium line is so strong and broad that we should have easily detected it if the lithium abundance in AFGL 2477 would be comparable to that in lithium rich stars.

Based on the above considerations we conclude that a HBB scenario and hence a single star scenario is very unlikely.

4.2. Two-star scenario

Above it was concluded that a single-star scenario is unlikely. Is the SED of AFGL 2477 the result of a coincidence in the sky or a binary system?

If it is a binary system then we have at the same distance two stars who differ a factor 120^{+230}_{-105} in luminosity, of which one is an infrared carbon star and the other a variable M6S star with a small mass loss rate. The distance between the stars is smaller than 3.7 10^{16} (d/kpc) cm, since both stars appeared in a 5″ aperture (Sect. 2). For the parameters of the C-star in Table 1 this implies that the MS star orbits the C-star well within the circumstellar wind of the C-star (at less than about 170 dust condensation radii). This gives two scenarios for the origin of the apparently enhanced s-process elements in the M6 star. The M giant is itself on the AGB (the variable character of the object is consistent with this) producing s-process elements in the interior, or the star has acquired s-process enhanced material by sweeping up the stellar wind of the C-star it orbits.

The first hypothesis is very unlikely. It implies that both stars are on the AGB. Since the AGB phase is short lived ($\lesssim 10^6$ yrs) this implies that the initial masses of the two objects must have been nearly identical (to within about 1%). It is difficult to imagine how the stellar properties could be so different now: the luminosities differ by at least a factor of 15, the mass loss rates by at least a factor of 1000, one is a carbon star while the other is an MS-star.

In the second scenario the lifetime problem does not need to occur since one can hypothesize that the M-star is on the RGB. The scenario of a mass-accreting M-star only works for an orbital separation that is small enough. One could use an infrared camera to obtain a better estimate of the separation between the M-star and the C-star. We also note that for small orbital separations the radial velocity changes may be quite large, and measurable depending on the inclination angle.

A coincidence in the sky seems to be a very reasonable alternative explanation as AFGL 2477 is only 1° from the galactic plane and the field is very crowded as can been seen in Fig. 2. The MS star is in this case probably a distant thermal pulsing AGB star. For $L = 4000\ L_{\odot}$ it is at 13 kpc and has a mass loss rate of 6.6 10^{-7} $M_{\odot}$/yr.

We end with the cautious note, that the mere presence of a bi-modal energy distribution is not sufficient evidence for the post-AGB nature of an object.

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