An Extremely Slow Nova?

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ABSTRACT
The binary companion to the peculiar F supergiant HD 172481 is shown to be a Mira variable with a pulsation period of 312 days. Its characteristics are within the normal range found for solitary Miras of that period, although its pulsation amplitude and mass-loss rate \( \dot{M} \sim 3 \times 10^{-6} \, M_\odot \, yr^{-1} \) are higher than average. Reasons are given for suspecting that the F supergiant, which has \( L \sim 10^4 \, L_\odot \), is a white dwarf burning hydrogen accreted from its companion.

Key words: binaries, novae, infrared: stars.

1 INTRODUCTION
HD 172481 is a high galactic latitude F-type supergiant which has drawn some attention since the IRAS survey showed it to have an infrared dust excess (Odenwald 1986). Reyniers & Van Winckel (2000, henceforth RVW) have since shown that the star is a spectroscopic binary with a cool M-giant companion. Their detailed spectroscopic analysis of the F supergiant indicates a moderate metal deficiency (\([\text{Fe/H}]=-0.55\)), no CNO-enhancement, a slight enhancement of s-process elements and high lithium content (\( \log (\epsilon(\text{Li})=3.6) \)). Essentially nothing was known about the M star prior to the present paper.

Since the IRAS measurements most authors have assumed that the F supergiant is a post-AGB star (RVW and references therein). This paper first discussed the nature of the M giant (section 3) and then, more speculatively, provides a possible explanation for the F supergiant (section 4).

2 PHOTOMETRY
The published Stromgren and Geneva photometry (Houk & Mermilliod 1998) indicate \( V \) between 8.9 and 9.1 while Geneva photometry from RVW shows that the visual magnitude is variable with a peak to peak amplitude of 0.22 mag. RVW show that the M star contributes about 10 per cent of the flux at \( V \) when the Mira is at maximum light (see below). The value, \( V=9.09 \, \text{mag} \), given in the SIMBAD database is used in the following analysis as representative of the mean light of the F star.

Forty-five \( JHKL \) measurements were made between 1988 and 1999 using the MkII photometer on the 0.75-m telescope at SAAO Sutherland. These are on the SAAO system (Carter 1990) and are listed in Table 1. They are accurate to about \( \pm 0.03 \, \text{mag} \) at \( JHK \) and \( \pm 0.05 \, \text{mag} \) at \( L \).

3 NATURE OF THE COOL STAR
A Fourier analysis of the data in Table 1 reveals a clear period of 312 days and light curves folded on this period are shown in Fig. 1. The peak to peak amplitudes of the Fourier fits to these variations are: \( \Delta J = 0.53 \), \( \Delta H = 0.68 \), \( \Delta K = 0.62 \) and \( \Delta L = 0.58 \) mag. These of course are lower limits to the amplitudes of the M giant as the F supergiant will contribute to the observed magnitude, particularly at the shorter wavelengths. Corrected amplitudes are discussed in section 3.1 and listed in Table 2.

These large amplitude variations clearly demonstrate that the M giant is a Mira variable and hence at the very tip of the Asymptotic Giant Branch (Feast & Whitelock 1987).

3.1 Infrared Colours
The reddening from HD 172481 has been estimated as \( E(B-V) = 0.44 \) (RVW) and 0.27 (Bersier 1996). In the following we calculate the magnitudes and colours using both of these values, generally giving the value for \( E(B-V) = 0.44 \) first and following it with the value associated with \( E(B-V) = 0.27 \), in brackets.

The first two lines of Table 2 list the magnitudes for HD 172481 at the Fourier maximum and minimum (note that, as seen in Fig. 1, the phase shifts between the \( JHKL \) light-curves are negligible). The next three lines have been corrected assuming a reddening of \( E(B-V) = 0.44 \) and give, respectively, the reddened corrected magnitudes of the F2Ia star (from Johnson 1966) on the assumption that this is the only significant contributor at \( V \), the reddening corrected mean magnitude of the Mira after the contribution from the F star has been removed, and the peak to peak amplitude of the Mira variations, also after removing the contribution of the F star. These three lines are then re-
Table 1. Observed Magnitudes

| JD  | J   | H   | K   | L   |
|-----|-----|-----|-----|-----|
| 7252.63 | 6.693 | 5.957 | 5.644 | 5.197 |
| 7270.65 | 6.671 | 5.918 | 5.606 | 5.138 |
| 7328.54 | 6.740 | 5.967 | 5.611 | 5.166 |
| 7334.49 | 6.742 | 5.997 | 5.606 | 5.138 |
| 7356.41 | 6.874 | 6.156 | 5.775 | 5.303 |
| 7362.43 | 6.934 | 6.224 | 5.821 | 5.422 |
| 7372.43 | 7.005 | 6.317 | 5.898 | 5.444 |
| 7383.42 | 7.059 | 6.384 | 5.965 | 5.510 |
| 7393.35 | 7.187 | 6.551 | 6.111 | 5.606 |
| 7422.34 | 7.196 | 6.544 | 6.094 | 5.553 |
| 7461.30 | 7.097 | 6.436 | 5.996 |
| 7617.64 | 6.687 | 5.878 | 5.499 | 4.922 |
| 7685.52 | 7.069 | 6.388 | 5.940 | 5.376 |
| 7698.48 | 7.106 | 6.437 | 6.002 | 5.357 |
| 7709.45 | 7.141 | 6.494 | 6.050 | 5.507 |
| 7719.46 | 7.167 | 6.518 | 6.092 | 5.557 |
| 7737.37 | 7.102 | 6.473 | 6.042 | 5.507 |
| 7742.45 | 7.128 | 6.477 | 6.050 | 5.541 |
| 7760.33 | 7.111 | 6.455 | 6.027 | 5.481 |
| 7767.31 | 7.095 | 6.437 | 6.020 | 5.444 |
| 7816.24 | 7.030 | 6.386 | 5.977 | 5.327 |
| 8054.57 | 7.211 | 6.580 | 6.133 | 5.559 |
| 8066.56 | 7.204 | 6.554 | 6.111 | 5.614 |
| 8093.53 | 7.139 | 6.479 | 6.050 | 5.437 |
| 8115.43 | 7.149 | 6.495 | 6.073 | 5.488 |
| 8166.35 | 6.856 | 6.130 | 5.751 | 5.177 |
| 8172.35 | 6.788 | 6.057 | 5.703 | 5.165 |
| 8451.48 | 7.017 | 6.341 | 5.937 | 5.336 |
| 8453.48 | 7.006 | 6.326 | 5.919 | 5.372 |
| 8853.36 | 6.617 | 5.820 | 5.461 | 4.953 |
| 9146.65 | 6.745 | 5.948 | 5.595 | 5.134 |
| 9223.42 | 6.876 | 6.174 | 5.793 | 5.276 |
| 9583.44 | 7.195 | 6.438 | 6.033 | 5.709 |
| 9615.39 | 7.229 | 6.589 | 6.167 | 5.568 |
| 9641.32 | 7.219 | 6.584 | 6.135 | 5.650 |
| 10238.57 | 7.251 | 6.615 | 6.201 | 5.691 |
| 10589.61 | 7.160 | 6.477 | 6.068 | 5.579 |
| 10716.35 | 6.607 | 5.795 | 5.429 | 4.915 |
| 10755.25 | 6.723 | 5.924 | 5.553 | 5.071 |
| 11100.27 | 6.905 | 6.239 | 5.808 | 5.398 |
| 11299.61 | 6.754 | 5.986 | 5.645 | 5.173 |
| 11388.40 | 6.788 | 6.068 | 5.684 | 5.202 |
| 11675.55 | 6.758 | 5.983 | 5.584 | 5.163 |
| 11711.57 | 6.904 | 6.178 | 5.759 | 5.222 |

Table 2. Mean Magnitudes

| component | V (mag) | J | H | K | L |
|----------|--------|---|---|---|---|
| max      | -      | 6.65 | 5.85 | 5.49 | 4.99 |
| min      | (9.09) | 7.18 | 6.53 | 6.11 | 5.57 |
| $-E(B-V) = 0.44$ | F2Ia | 7.75 | 7.21 | 7.04 | 7.00 | 6.95 |
| $-E(B-V) = 0.27$ | Mira (mean) | - | 7.58 | 6.58 | 6.08 | 5.47 |
| $\Delta$ | - | 1.3 | 1.1 | 0.9 | 0.7 |
| $E(B-V) = 0.27$ | F2Ia | 8.27 | 7.73 | 7.56 | 7.52 | 7.47 |
| $\Delta$ | - | 0.9 | 0.9 | 0.8 | 0.7 |

Figure 1. The infrared observations for HD 172481 phased on a period of 312 days, with an arbitrary zero-point of JD 2440000; each point is plotted twice.

It is instructive to compare the colours deduced for this Mira with those of normal isolated Miras. Whitelock, Marang & Feast (2000, henceforth WMF) provide $JHKL$ observations of Miras with thin dust shells, while Whitelock et al. (1994) do the same for IRAS selected Miras with relatively thick shells. The mean colours of the Mira are listed in Table 3 together with those of a typical 312 day Mira, calculated from equations 1 to 4 of WMF.

The deduced colours are obviously somewhat uncertain, particularly at $J$, because of the uncertain correction for the F star. Nevertheless, they fall within the range shown by normal unreddened Miras. In particular, $K-L$, although larger than the mean calculated from WMF equation 3, is within the range shown by normal Miras. WMF note a strong correlation between the pulsation amplitude and $K-L$, and indeed the pulsation amplitude of this Mira is high.

This Mira is of particular interest in view of the fact that we can infer its metallicity; only a very small number of Miras, those associated with globular clusters, have reliable metallicities. RVW estimated $[\text{Fe/H}]=-0.55$ for the F supergiant which we might reasonably assume also applies to the Mira. For comparison, Table 3 gives the colours (from WMF) of the Mira V3 in NGC 5927 which has a 311 day period and $[\text{Fe/H}]=-0.37$ (Harris 1996).

Table 3. Mean Magnitudes

| component | V (mag) | J | H | K | L |
|----------|--------|---|---|---|---|
| max      | -      | 6.65 | 5.85 | 5.49 | 4.99 |
| min      | (9.09) | 7.18 | 6.53 | 6.11 | 5.57 |
| $-E(B-V) = 0.44$ | F2Ia | 7.75 | 7.21 | 7.04 | 7.00 | 6.95 |
| $-E(B-V) = 0.27$ | Mira (mean) | - | 7.58 | 6.58 | 6.08 | 5.47 |
| $\Delta$ | - | 1.3 | 1.1 | 0.9 | 0.7 |
| $E(B-V) = 0.27$ | F2Ia | 8.27 | 7.73 | 7.56 | 7.52 | 7.47 |
| $\Delta$ | - | 0.9 | 0.9 | 0.8 | 0.7 |
Table 3. Mean Colours of various components

| star     | $J - H$ | $H - K$ | $K - L$ | $J - K$ | $E(B - V)$ |
|----------|---------|---------|---------|---------|-----------|
| Mira     | 1.00    | 0.50    | 0.61    | 1.50    | 0.44      |
| Mira     | 0.88    | 0.43    | 0.59    | 1.31    | 0.27      |
| $P = 312$| 0.94    | 0.44    | 0.51    | 1.38    |           |
| N5927 V3 | 0.95    | 0.39    | 0.52    | 1.34    |           |

3.2 Mass-loss Rate

As RVW discussed, HD 172481 was detected by IRAS and shows an obvious infrared excess. The colour corrected 12.0μm mag is $[12] = 1.76$, so $K - [12] = 4.3$ (4.2). This is larger than values shown by any of the stars discussed by WMF, but is within the range found for IRAS Miras by Whitelock et al. (1994). This $K - [12]$ would imply a mass-loss rate of $\dot{M} \sim 3 \times 10^{-6} M_\odot yr^{-1}$ (Whitelock et al. 1994 fig 21) which is high for a 312 day Mira, but higher mass-loss rates are usually associated with larger pulsation amplitudes and again we note that the pulsation amplitude of this star is high.

It would therefore seem possible that the dust shell, which is responsible for large $K - [12]$ and presumably for the circumstellar extinction, originates entirely from the Mira. While it is not essential to assume that any of the dust is associated with the F supergiant, we cannot rule out the possibility that some of it is. Neither can we rule out the possibility of dust trapped in a circumbinary disk, as has been proposed for some other supposed post-AGB binary systems (e.g. Waters et al. 1993; Van Winckel 1999).

Note also that the IRAS colours of HD 172481 are within the range found for D-type symbiotics (Whitelock 1988), illustrating the similarity of their dust shells (see section 4).

3.3 Distance and Luminosity

The distance modulus of the Mira can be calculated via the period luminosity relation (Whitelock & Feast 2000):

$$M_K = -3.47 \log P + 0.84,$$

to give $(K_0 - M_K) = 13.9$ (13.8) or a distance of 6.0 (5.7) kpc, and a height above the galactic plane of $-1.1$ ($-1.0$) kpc.

The bolometric magnitude of the Mira can be established by fitting a blackbody to the $JHKL$ flux (see Robertson & Feast 1981). This gives a bolometric magnitude at mean light of 9.30 (9.09) and at maximum light of 8.72 (8.64). Or in absolute terms at mean light $M_{bol} = -4.59 (-4.69)$ and $L_M = 5.3 \times 10^3 (5.8 \times 10^3) L_\odot$.

4 THE F SUPERGIANT

RVW established that the relative luminosities of the F supergiant and the M star are $L_F/L_M = 1.8$, for a reddening of $E(B - V) = 0.44$ (or $L_F/L_M = 1.0$ for $E(B - V) = 0.2$). The near-infrared measurement which they used to define the flux of the system was obtained on JD2448850 ($K = 5.48$ Van Winckel, private communication), i.e. at maximum light for the Mira. Thus the luminosity of the F star is $L_F = 1.6 \times 10^4 L_\odot (0.9 \times 10^4 L_\odot)$.

RVW argue that the F supergiant is a post-AGB star on the basis of its high galactic latitude, large radial velocity and moderate metal deficiency. In support of this they also mention the dust, a variable Hα profile and a slight overabundance of s-process elements. Our identification of the M star as a Mira variable confirms the binary as a low mass system. There is, however, an alternative to the post-AGB star scenario. The F supergiant could be a white dwarf, with hydrogen-shell burning of material accreted from the Mira wind providing a pseudo-photosphere and the observed luminosity.

Iben & Tutukov (1996) discuss the evolution of mass accreting white dwarfs in wide binaries, such as symbiotic stars. Of particular interest in the present context are the D-type symbiotics where a white dwarf accretes from the wind of a Mira variable in a binary system with a period in excess of about 10 years (Whitelock 1987). In certain cases the accretion rates are such that a thermonuclear runaway gives rise to a very slow nova, e.g. RR Tel and V1016 Cyg.

These symbiotic stars, with their high excitation emission lines, are apparently very different from HD 172481. However, it is clear from Iben & Tutukov that relatively small differences, e.g. in the accretion rate of the white dwarf, can give rise to very different phenomena.

The luminosity derived above, $L_F \sim 10^4 L_\odot$, is that expected for a cool $\sim 0.6 M_\odot$ white dwarf in a hydrogen shell burning phase following a hydrogen shell flash (see Iben & Tutukov fig. 5).

A very rough estimate of the accretion rate of the white dwarf can be derived from Iben & Tutukov’s equation 2. If we assume the mass-loss rate from the Mira (section 3.2), a $0.6 M_\odot$ white dwarf, a total stellar mass (white dwarf plus Mira) of $1.5 M_\odot$, a wind velocity of $20 \text{ km s}^{-1}$ and an orbital period of 10 years, the derived accretion rate onto the white dwarf is $2 \times 10^{-7} M_\odot \text{ yr}^{-1}$.

It is clear from fig. 7 of Iben & Tutukov that this rate would in fact result in steady hydrogen burning on the surface of the white dwarf. However, for the parameters assumed this rate should probably be regarded as an upper limit, as Iben & Tutukov’s equation 2 is based on Bondi-Hoyle accretion and other estimates lead to significantly (up to ten times) lower values (e.g. Theuns, Boffin & Jorissen 1996; Mastrodemos & Morris 1999). Furthermore, plausible changes in the period or the wind velocity could increase or decrease the rate. Nevertheless it seems likely that a white dwarf paired with this Mira would accrete mass in such a way as to either burn it steadily or in shell flashes, for a large range of stellar separations.

In discussing the nova phenomenon Iben & Tutukov point out that in wide binaries there is no reason to expect the loss of the hydrogen envelope after the explosion. So that it is possible for the newly created supergiant to last for several decades. This might explain the present condition of the F supergiant in HD 172481.

The high abundance of lithium in the supergiant spectrum (RVW) may well be key to understanding this system. Arnould & Nørgaard (1975) and Starrfield et al. (1978) predict the formation of large quantities of lithium during hydrogen-burning thermonuclear runaways. However, their calculations are not obviously applicable to the situation under discussion and they also predict an overabundance of carbon and nitrogen which are not found in HD 172481 (RVW). More recently Hernanz et al. (1996) predict signif-
icant lithium production from some nova models, but these seem to underestimate the ejecta masses. Clearly more theoretical work is required in this area.

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