VY Canis Majoris: The Astrophysical Basis of Its Luminosity

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ABSTRACT

The luminosity of the famous red supergiant VY CMa (\(L \sim 4 - 5 \times 10^5L_{\odot}\)) is well-determined from its spectral energy distribution and distance, and places it near the empirical upper luminosity limit for cool hypergiants. In contrast, its surface temperature is fundamentally ill-defined. Both contradict a recent paper by Massey, Levesque and Plez (2006). Implications for its location on the HR Diagram and its apparent size are discussed.

Subject headings: stars: late–type — stars: individual(VY CMa) — supergiants

1. Introduction

Massey, Levesque & Plez (2006) suggest that the famous red supergiant VY CMa is nearly a factor of 10 less luminous than has previously been stated by several authors. They assert that its high luminosity and other “extreme” properties such as its inferred large size were based on an adopted effective temperature that was too low (e.g. \(\sim 2800^\circ\), Le Sidaner & LeBetre (1996)).

Massey et al fit recent optical spectrophotometry of VY CMa with MARCS model atmospheres and derive a much warmer effective temperature. Combining its apparent visual magnitude, an adopted interstellar extinction, and a temperature dependent bolometric correction, they derive a luminosity \(L \sim 6 \times 10^4L_{\odot}\) instead of the usually quoted \(L \sim 5 \times 10^5L_{\odot}\). However this classical approach ignores one of VY CMa’s distinguishing characteristics, its spectral energy distribution and large excess radiation in the infrared. In this brief paper I discuss VY CMa’s energy distribution, its resulting luminosity and location on the HR Diagram.

2. The Energy Distribution and Luminosity

Figure 1 shows VY CMa’s spectral energy distribution from 0.5 to 100 \(\mu\)m. The data are based on recent photometry in Tables 3 and 4 in Smith et al (2001) plus the IRAS fluxes from
25 to 100 \(\mu m\). Although VY CMa is an irregular variable in the visual, its long wavelength fluxes have shown only small variability. Most of the star’s radiation is reprocessed by the dust in its extensive circumstellar ejecta. I therefore used the total fluxes integrated over the entire nebula for Figure 1. Its energy distribution rises rapidly in the infrared and has a broad maximum between 5 and 10 \(\mu m\). Integrating the apparent energy distribution yields a luminosity of \(L = 4.3 \times 10^5 L_\odot\) at VY CMa’s distance of 1.5 kpc (Herbig 1972, Lada & Reid 1978, Marvel 1997, the same distance used by Massey et al.) If corrected for interstellar extinction at visual and red wavelengths, the luminosity would increase by a few percent.\(^1\)

The standard “textbook” approach, relying only on visual photometry and spectroscopy and an assumed temperature, is not valid for stars with sufficient circumstellar dust to reradiate their visual and red flux in the thermal infrared. In some cases, the radiating dust also dominates the radiation between 1 \(\mu m\) and 5 \(\mu m\) and contributes significant circumstellar extinction at visual, red and near-infrared wavelengths. Other well-studied examples in our galaxy are VX Sgr, S Per, and NML Cyg. Like VY CMa, all three are strong maser sources and NML Cyg is optically obscured. See Schuster, Humphreys & Marengo (2006) for recent images of these stars.

In summary, the luminosity proposed for VY CMa by Massey et al is far less than what is actually observed, and there is little doubt that it is near the empirical upper luminosity limit for the cool hypergiants (Humphreys & Davidson 1979, 1994).

3. Discussion – VY CMa on the HR Diagram

There is general consensus that VY CMa is a red supergiant. Its high luminosity is well-determined from its spectral energy distribution and distance. Further consideration of its exact position on the HR Diagram depends on the assumed surface temperature. Previously published spectral types for VY CMa in the past 30 years or so have been mostly in the M4-M5 range; however, Massey et al suggest that VY CMa’s apparent spectral type is more likely \(\sim M2.5\) based on the MARCS model atmosphere fit to their spectrum. Interestingly, though, the blue TiO bands in their published spectrum (Figure 2 in Massey et al) are more like their M4-type reference spectrum than the M2-type spectrum they show. This author’s numerous spectra of VY CMa obtained over many years have all been in the M4-M5 range.

\(^1\)Essentially the same luminosity is obtained whether or not a correction for interstellar extinction is applied because most of the flux is escaping at \(\sim 10\mu m\). Furthermore, an \(A_v\) of 3.2 mag (Massey et al) implies that at least 2 mag of more of circumstellar extinction is required in the visual to equal the flux emitted at 10\(\mu m\). The wavelength dependence of the CS extinction correction, however, is not known.
Adopting this spectral type with the temperature scale proposed by Levesque, et al (2005) gives $T_{\text{eff}} \sim 3450-3535\degree$, while an older scale (used in Humphreys & McElroy 1984 from Flower 1977) yields $T_{\text{eff}} \sim 3200\degree$ for an M4-M5 star.

However, one should be cautious in the case of VY CMa; we are not observing either its photosphere or its surface directly. It has been known for some time that VY CMa’s absorption spectrum is significantly redshifted with respect to its systemic velocity (Humphreys 1975, Wallerstein 1977) due to scattering by dust (Herbig 1970, Kwok 1976, Van Blerkom & Van Blerkom 1978). Indeed, most of VY CMa’s visual-red radiation originates by reflection and scattering by the dust grains at 100 AU from the star, the dust formation radius. Only a few percent of the radiation actually escapes through the dust shell, which is very likely inhomogeneous, implying optical depths of 4 to 5 at $\sim 7000\AA$ in its wind (Humphreys et al 2005). If the wind is opaque, then $R_{\text{ph}}$ where the photons arise, could be larger than the true stellar radius, and the underlying star possibly somewhat warmer.

Massey et al also suggest that with previous temperature estimates, VY CMa would violate the Hayashi limit. But the cause of the apparent conflict with the Hayashi limit is the assumed temperature not the luminosity. Whether or not it violates the Hayashi limit depends on whether the adopted temperature, inferred from the strength of the TiO bands or an atmospheric model, is indicative of the star’s ill-defined surface or its wind. With the above temperatures, VY CMa is on the edge or just inside the Hayashi limit as plotted in Figure 1 in Massey et al., but the standard Hayashi limit applies to hydrostatic atmospheres. Non-spherical outflows and a resulting dense wind as in VY CMa may affect the Hayashi limit’s location on the HR Diagram. In this regard, note that on this same figure, at their preferred luminosity for VY CMa, the star is also right on the edge of the Hayashi limit.

Another of Massey et al’s problems with VY CMa is its large size. They point out, however, that Monnier et al (2004) derived a radius of 3000 $R_\odot$ from 2 $\mu$m interferometry. Monnier himself, in the Massey et al paper, offered a couple of possible explanations for the apparent large size, including significant structure in the dust shell on the scale of the stellar diameter. This is probably correct (Humphreys et al 2005). Given my arguments above, 3000 $R_\odot$ is probably not the actual size of the imbedded star. Adopting this radius with VY CMa’s luminosity gives an “effective” temperature of $\sim 2700\degree$ which Massey et al say is too low. Alternatively, with the apparent temperatures given above, the radius is 1800 to 2100 $R_\odot$. In either case, VY CMa is obviously very luminous, cool and big.
4. Concluding Remarks

With its extraordinary high mass loss rate \( (2 - 3 \times 10^{-4} M_\odot \text{yr}^{-1}) \), Danchi et al 1994), extensive circumstellar ejecta and discrete ejection episodes over the past 1000 yrs (Smith et al 2001, Humphreys et al 2005), VY CMa is undoubtedly not in hydrostatic equilibrium. Its extreme characteristics, strong wind and evidence for surface activity are more easily appreciated at its position near the upper luminosity boundary in the HR Diagram and near the Hayashi limit, than as a less luminous red supergiant \((\sim 15M_\odot)\) as Massey et al suggested.

VY CMa is not alone. In previous papers (Humphreys et al 1997, Smith et al 2001) I have pointed out that about 10 known M-type supergiants in the Milky Way and Local Group galaxies have \(M_{bol}\) brighter than -9 mag. About half of these stars, in the Milky Way and in the LMC, are known OH/IR stars with strong maser emission some of which are optically obscured. We do not know if this is a short–lived high mass loss phase that all red supergiants pass through similar to the optically obscured carbon and M stars near the top of the AGB, or if it occurs only in the most massive ones, due perhaps to enhanced instability near the upper luminosity boundary. Present observations of VY CMa do not let us distinguish whether it is in the process of creating an optically thick cocoon or expelling it in transition back to warmer temperatures. VY CMa is undoubtedly one of the most important stars for understanding the high mass loss episodes in the final stages of massive star evolution.

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Fig. 1.— The spectral energy distribution of VY CMa. The solid circles are fluxes measured from HST optical images and near-IR groundbased images (Table 3 in Smith et al (20010), the open squares are standard broadband IR photometry (Table 4 in Smith et al (2001), and the +’s are the IRAS 12 to 100µm fluxes.