

# HD 5980: wind collisions and binary star evolution

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HD 5980 is a multiple system containing at least 3 very massive and luminous stars. Located in the Small Magellanic Cloud, it is an ideal system for studying the massive star structure and evolutionary processes in low-metallicity environments. Intensely observed over the past few decades, HD 5980 is a treasure trove of information on stellar wind structure, on wind-wind collisions and on the formation of wind-blown circumstellar structures. In addition, its characteristics suggest that the eclipsing WR+LBV stars of the system are the product of quasi-homogeneous chemical evolution, thus making them candidate pair production supernovae or GRB progenitors. This paper summarizes some of the outstanding results derived from half a century of observations and recent theoretical studies.

## 1 Variable wind structure and wind collisions

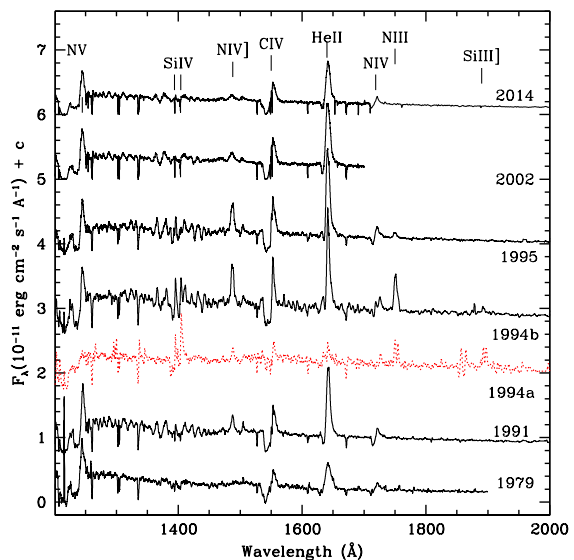
The most prominent components of the HD 5980 system are the eclipsing binary pair, *Star A* and *Star B* ( $P_{\text{orb}}=19.3\text{d}$ ,  $e=0.3$ ), both of which currently have a Wolf-Rayet type spectrum. *Star A* became the dominant component after the 1994 eruption, an event similar to the major eruptions observed in Luminous Blue Variables. A third component that is observed in the spectrum, *Star C*, is an O-type star with photospheric absorption lines indicating a highly eccentric orbit ( $P=97\text{d}$ ,  $e \sim 0.8$ ; Schweickhardt 2000; Koenigsberger et al. 2014). A review of the pre-eruption and eruption properties is given in Koenigsberger (2004) and references therein.

Available spectroscopic observations date back to 1956 in the optical and to 1978 in the UV. An outstanding result concerns  $v_{\infty}$ , the terminal wind velocity of *Star A*. Its value declined from  $\sim 3000 \text{ km s}^{-1}$  in 1979 to  $\sim 300 \text{ km s}^{-1}$  during the 1994 eruption, increasing thereafter. By 2014, it had once again attained speeds similar to those of 1979. These observations provide a unique testing ground for wind theory, specifically:

a) *Wind-blown circumstellar structures.* The interaction that occurs when a fast wind catches up and collides with a slow wind that was emitted previously is predicted to produce an expanding shell with a particular velocity structure. The very early stage of this phenomenon associated with the 1994 eruption was observed in HD 5980 (González & Koenigsberger 2014). A tantalizing possibility is that this event was not an isolated one, but that it re-occurs on a  $\sim 40$  year timescale (Koenigsberger et al. 2010), in which case the circumstellar vicinity of HD 5980 might be highly structured, with concentric high and low density regions.

b) *Binary wind-wind interaction.* The characteristics of the region where the winds of two stars collide are determined by the orbital separation, wind velocities and mass-loss rates. HD 5980 offers the extraordinary opportunity for studying this phenomenon in a system in which one of the two winds changes in a

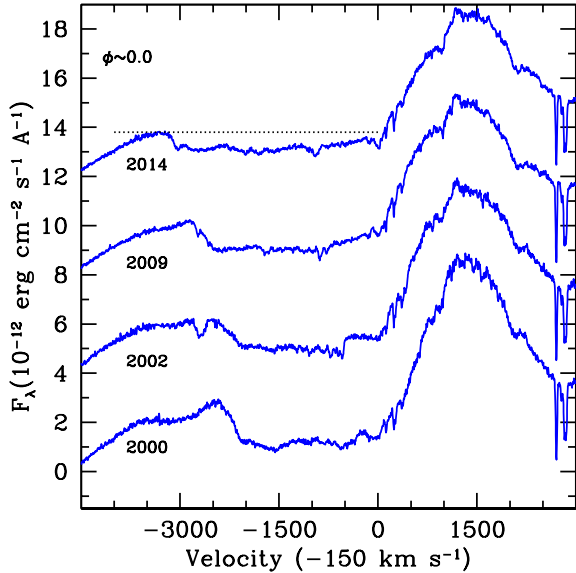
known manner over time. Thus, the morphology and strength of the interaction region may be predicted, and observable diagnostics compared with the actual observations. For example, the opening angle of the wind collision shock cone must have varied over time due to the changing wind momentum of *Star A*. By tracing spectral features over orbital phase at different epochs, the potential exists for answering the question of how much optical emission is produced in the shock cone region which, in turn, may help constrain the cooling efficiency.



**Fig. 1:** UV spectra of HD 5980 obtained in 1979–1995 by *IUE* and 2002–2014 by *HST/STIS*. The spectrum during the maximum of the 1994 eruption was very similar to that of a B1.5I<sup>+</sup> star, but transitioned rapidly through WNL and into WN5-6.

c) *Stellar wind structure.* Empirical correlations have emerged from the UV observations of HD 5980 that relate wind velocity, continuum intensity and emission-line strengths (Georgiev et al. 2011). Com-

bined with the determination of luminosity ( $L$ ), radius ( $R$ ) and mass-loss rate ( $\dot{M}$ ) from wind models for each of the corresponding epochs, the wind driving mechanisms may be directly tested. For example, we have found that the 1994 eruptive process involved an increase in  $L$  and  $\dot{M}$  and a decrease in  $v_\infty$ .



**Fig. 2:** Montage of the N v 1238/1242 P Cygni profile for the 4 epochs for which *HST/STIS* observations were acquired during the eclipse of *Star B* by *Star A* and thus reflect the wind velocity of the latter. The abscissa is given in velocity measured from the laboratory wavelength of the N v 1238 Å line, corrected for the velocity of the SMC in the HD 5980 vicinity. Note the increasing extent of the flat bottom region in the P Cygni absorption, which provides a measure of the maximum wind speed.

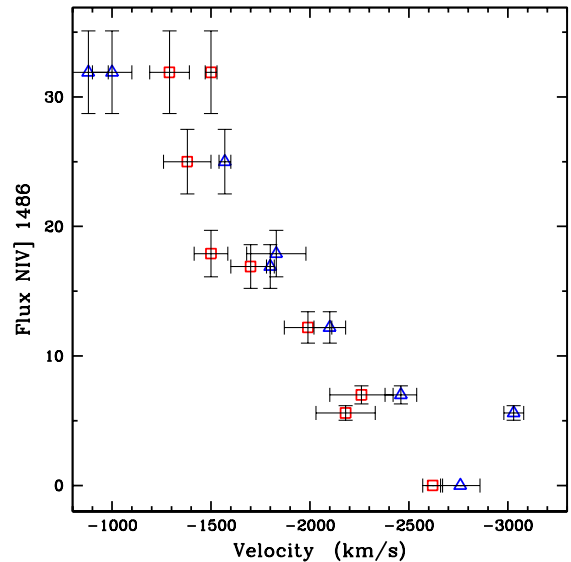
## 2 Evolutionary state

HD 5980 is clearly a system that is in its late stages of evolution, as can be concluded from the enrichment of surface layers with nuclear-processed elements and the LBV-type behavior. The orbital solution for the *Star A* + *Star B* binary was recently refined by Koenigsberger et al. (2014), who also discussed its evolutionary state and concluded that the most likely scenario is one in which *Star A* and *Star B* are following a quasi-homogeneous chemical evolution track.

Yoon et al. (2006) discussed the role of chemically homogeneous evolution in the context of the progenitor formation of slow gamma ray burst (GRB) sources and Langer et al. (2007) discuss it in the

context of pair creation supernovae. A requirement for such models is the presence of an efficient mixing mechanism during most of the stellar lifetime which, in single stars, is rapid rotation. For binary stars, the usual hypothesis is that the stellar rotation synchronizes with the orbital angular velocity, thus leading to relatively slow rotation in binaries such as HD 5980. However, the relatively large orbital eccentricity of this system precludes synchronization, in the strict sense of the term.

Non-synchronous binary stars undergo perturbations that, one may speculate, could contribute to internal mixing in a manner as efficient as rapid rotation (Koenigsberger & Moreno 2013). Thus, a plausible argument can be made that *Star A* and *Star B* in HD 5980 are, indeed, following quasi-homogeneous chemical evolutionary tracks.



**Fig. 3:** Correlation of line strength vs. wind velocity. The N iv] 1486 Å emission-line flux obtained from *IUE* and *HST* observations is plotted against the wind velocity derived from P Cygni absorption profiles. Plotted are only the data from spectra obtained when *Star A* is in front of *Star B*. Squares correspond to the edge-velocity of He II 1640 Å and triangles correspond to the saturated portion of N v 1238 Å. The abscissa is un-reddened flux in units of  $10^{12} \text{ erg cm}^{-2} \text{ s}^{-1}$ .

*Acknowledgements:* I thank Norbert Langer for many helpful discussions and Ulises Amaya for computing support. This work was funded by UNAM/PAPIIT grant 105313 and CONACYT grant 129343. Spectra reported in this paper were obtained with the *International Ultraviolet Explorer*, and by the *Hubble Space Telescope*. *HST* is operated by the Space Telescope Science Institute, which is

operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555.

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