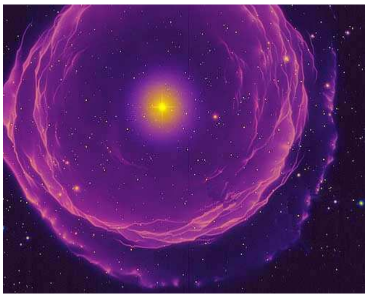
# Spectroscopy of the $\rho$ Cas Millennium Outburst



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## Summary

An exceptional variability phase occurred in the peculiar F-type hypergiant $\rho$ Cas ($\mathrm{Ia}^+$) when the $V$ brightness dimmed by about a full magnitude between June and September 2000. The star recovered from this deep minimum by April 2001. It is the third outburst of $\rho$ Cas on record in the last century.

We detect the formation of TiO bands in high-resolution spectra obtained from our long-term monitoring campaigns over the past decade with the Utrecht Echelle Spectrograph on the William Herschel Telescope, and the Sofin spectrograph of the Nordic Optical Telescope (La Palma). Optical and near-IR TiO bandheads, i.e. from the $\gamma$-system 0-0 transition at 7050 Å, develop in the summer of 2000. TiO formation in the outer atmosphere occurred before the deep brightness minimum. The TiO shell is driven supersonically with $\dot{M}\simeq 2.5\,10^{-2}\,M_{\odot}\,yr^{-1}$ as $T_{\rm eff}$ decreases by at least 3000 K. Strong episodic mass loss and TiO have also been observed during the outbursts of 1945-47 and 1985-86. A preliminary analysis of these exceptional spectra is presented, by comparing them with high-resolution optical spectra of the early M-type supergiants $\mu$ Cep (Ia) and Betelgeuse (Iab). Central emission is observed above the local continuum level in the split Na $D$ lines. An analysis of $\rho$ Cas' optical emission line spectrum is provided in **Lobel (1997), Pulsation and Atmospherical Instability of Luminous F- and G-type Stars**, Maastricht: Shaker.

We propose the formation of a low-temperature, optically thick shell of 1.4 $10^{-2}\,M_{\odot}$ during $\sim$200 d, caused by instability of the upper atmosphere of this pulsating massive supergiant near the Eddington luminosity limit (Lobel 2001, ApJ, 558, 780). A recent review is at HTTP://XXX.LANL.GOV/FORMAT/ASTRO-PH/0108358

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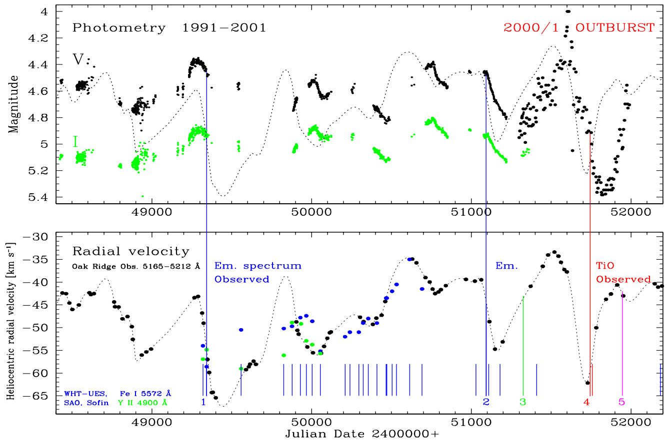



**Fig. 1 Upper panel:** Photo-electric observations of $\rho$ Cas in $V$ (BLACK DOTS) and $I$ (GREEN DOTS) by Percy, Kolin, and Henry (PASP, 112, 363, 2000) over the past decade, are supplemented with visual magnitudes from $AFOEV$ during the outburst of late 2000. The light curve shows rather irregular (semi-regular at best) variability, with the deep outburst minimum ($V\sim5^{\rm m}.3$) in Sept-Nov 2000, preceded by a conspicuously bright maximum ($V\sim4^{\rm m}$) in March 2000. **Lower Panel:** The radial velocity curve has been monitored in the optical at the Oak Ridge Observatory (CfA) (BLACK DOTS). A cubic spline fit to these velocity data (DOTTED LINE) is compared with the $V$ magnitude in the upper panel. We find that the star becomes brightest for variability phases when the atmosphere rapidly expands ($V_{\rm rad}$ decreases by $\sim$20 $\mathrm{km\,s^{-1}}$ in less than 200 d). The colored vertical lines indicate high resolution echelle spectroscopic observations. Numbered spectra are discussed below.

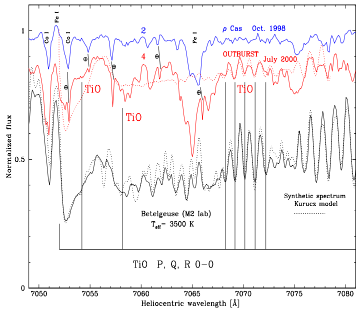



**Fig. 2** TiO absorption $\gamma$- system bands observed in the outburst spectrum of $\rho$ Cas of July 2000. The spectrum synthesis with only TiO lines is shown by the red dotted line. A best fit is obtained with a Kurucz model atmosphere of $T_{\rm eff}$=3750 K and log($g$)=0.0. These characteristic TiO bands are also observed in Betelgeuse (M2) with $T_{\rm eff}$=3500 K (VERTICAL LINES). The synthesis typically contains $\sim$1500 TiO lines per Å. The TiO bands in $\rho$ Cas indicate the formation of a cool, optically thick, circumstellar shell with $T$<3000 K, caused by the rapid expansion of the outer atmosphere during the outburst. We observe an expansion velocity of 32±2 $\mathrm{km\,s^{-1}}$ for these TiO bands, which is 15-20 $\mathrm{km\,s^{-1}}$ faster than determined from atomic photospheric lines.

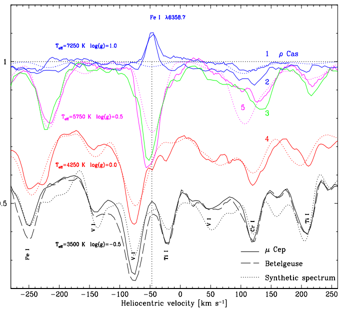



**Fig. 3** A best fit to the atomic spectrum observed during the outburst is computed with $T_{\rm eff}$=4250 K (RED DOTTED LINE). The graph is centered around the Fe I and V I blend at $\lambda$6358. The vertical dotted line is the $\rho$ Cas rest velocity of $-47$ $\mathrm{km\,s^{-1}}$. The entire photospheric spectrum shifts blueward during the outburst, developing many atomic absorption features also observed in Betelgeuse and $\mu$ Cep (BLACK LINES). We observe metal emission lines above the stellar continuum level during two phases of very fast atmospheric expansion in Dec. '93 (1) and Oct. '98 (2). The fast wind collides with circumstellar material which excites the permitted emission spectrum. For this phase we compute $T_{\rm eff}$=7250 K (BLUE DOTTED LINE), which reveals a decrease in $T_{\rm eff}$ of at least 3000 K during the outburst.

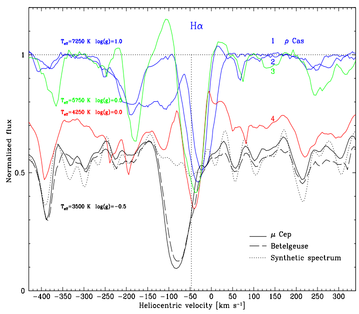



**Fig. 4** From synthetic spectrum fits to the TiO bands we determine a mass-loss rate of $\dot{M}\simeq2.5\,10^{-2}\,M_{\odot}\,yr^{-1}$ during the outburst of $\rho$ Cas in late 2000. We compute that the spectrum returned to $T_{\rm eff}$=5750 K within 100 d after the deep outburst minimum (MAGENTA LINES IN FIGS. 1 AND 3) with an increase of light $\sim0^{\rm m}.5$. During the outburst the H$\alpha$ profile shows prominent emission peaks (indicating large $\dot{M}$) around a central absorption core which is only weakly blueshifted. In May '99 (3) we observe a prominent inverse P-Cygni profile, indicating an exceptional phase of very strong downflow before the brightness maximum of March 2000 preceding the outburst.

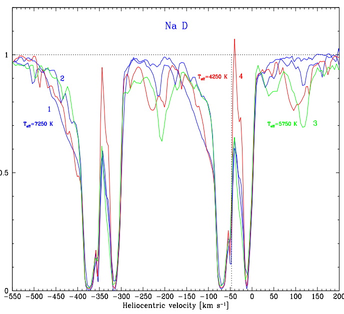
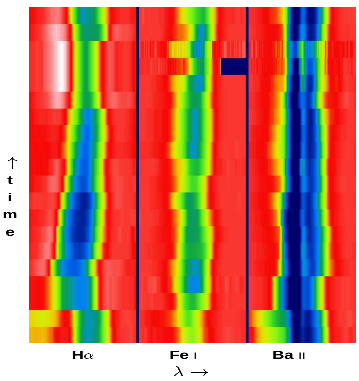



**Fig. 5** We observe core emission in the Na $D$ absorption lines with central maxima **above** the local continuum level during the outburst. It results from the strong decrease of the photospheric continuum flux due to the decrease of $T_{\rm eff}$ by at least 3000 K. Since we observe TiO **before** the deep light minimum, this minimum cannot not result from veiling by TiO or other molecules. The light minimum results from a strong decrease of the entire atmospheric temperature structure. The Na $D$ lines are intensity saturated and do not reveal Doppler shifts. The far violet extended line wings form in an optically thick wind during fast expansion.



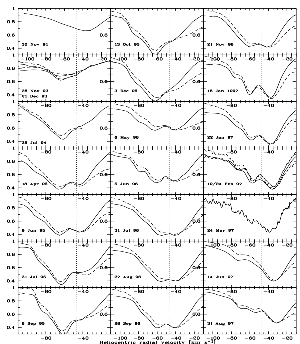



**Fig. 6** Dynamic spectra of H$\alpha$, Fe I $\lambda$5572, and Ba II $\lambda$6141 line profiles (from left to right), observed between late 1993-97 (time runs upward). Red is the stellar continuum level. We observe that the H$\alpha$ absorption core weakens and shifts redward. H$\alpha$ develops blue emission wings (white), indicating a collapse of the larger circumstellar envelope. The Fe I line forms in the deeper photosphere showing two pulsation cycles, with shorter $V_{\rm rad}$ changes. The split Ba II line shows static central emission, with adjacent variable absorption cores. **Fig. 7** The split Fe I $\lambda$5506 (solid line) and $\lambda$5501 (dashed) lines reveal opposite intensity changes in both absorption cores due to pulsations. The static central emission forms far from the pulsating photosphere (Lobel 1997).

### Conclusions on $\rho$ Cas 2000/1 outburst

- TiO shell observed before light minimum
- Supersonic $V_{\rm rad}$ expansion while dimming
- TiO shell expands faster than photosphere
- $\dot{M}\simeq2.5\,10^{-2}\,M_{\odot}\,yr^{-1}$ during outburst
- $T_{\rm eff}$ decreases from 7250 to <3750 K
- $T_{\rm eff}$ returns to 5750 K within 100 d
- Prominent emission line spectrum observed in phases of fast wind expansion
- Large oscillation cycle and very bright light maximum precede the outburst
- The outburst can be driven by release of hydrogen recombination energy