MASS-LOSS AND RECENT SPECTRAL CHANGES IN THE YELLOW HYPERGIANT ρ CASSIOPEIAE

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Abstract

The yellow hypergiant ρ Cassiopeiae (F-G Ia0) has recently become very active with a tremendous outburst event in the fall of 2000. During the event the pulsating supergiant dimmed by more than a visual magnitude, while its effective temperature decreased from 7000 K to below 4000 K over about 200 d, and we directly observed the largest mass-loss rate of about 5% of the solar mass in a single stellar outburst so far. Over the past three years since the eruption we observed a very prominent inverse P Cygni profile in Balmer Hα, signaling a strong collapse of the upper atmosphere, also observed before the 2000 event. Continuous spectroscopic monitoring reveals that the Hα line profile has transformed into a P Cygni profile since June 2003, presently (Sept 2004) signaling supersonic expansion velocities up to $\sim$120 km s^{-1} in the extended upper atmosphere, comparable to the 2000 outburst. With the new fast atmospheric expansion many strong neutral atomic emission lines have appeared in the optical and near-IR spectrum over the past half year.

Based on the very recent unique spectral evolution we observed the far-UV spectrum with the *FUSE* satellite in July 2004. The *FUSE* spectrum reveals that high-temperature plasma emission lines of O VI and C III are absent in the hypergiant, also observed for the red supergiant α Ori (M2 Iab). On the other hand, we observe prominent transition region emission lines in the smaller (less luminous) classical Cepheid variable β Dor (F-G Iab-Ia), indicating that the mean atmospheric extension and surface gravity acceleration (as compared to effective temperature and atmospheric pulsation) play a major role for the formation of high-temperature stellar atmospheric plasmas. We present an overview of the recent spectral variability phases of ρ Cas with enhanced mass-loss from this enigmatic cool star.

Key words: Stars: ρ Cassiopeiae – stellar winds – pulsation – mass-loss – spectroscopy – supergiants – emission lines

1. Introduction

ρ Cas is a cool *hypergiant*, one of the most luminous cool massive stars presently known. Yellow hypergiants are post-red supergiants, rapidly evolving toward the blue supergiant phase. They are among the prime candidates for progenitors of Type II supernovae in our Galaxy. This type of massive supergiant is very important to investigate the atmospheric dynamics of cool stars and their poorly understood wind acceleration mechanisms that cause excessive mass-loss rates above 10^{-5} M$_\odot$ yr^{-1} (Lobel et al. 1998). These wind driving mechanisms are also important to study the physical causes for the luminosity limit of evolved stars (Lobel 2001a; de Jager et al. 2001). ρ Cas is a rare bright cool hypergiant, which we are continuously monitoring with high spectral resolution for more than a decade (Lobel 2004). Its He-core burning phase is accompanied by tremendous episodic mass-loss events, which we recently observed with a new outburst between 2000 July and 2001 April (Lobel et al. 2003a).

In quiescent pulsation phases ρ Cas is a luminous late F-type supergiant (Lobel et al. 1994). During a tremendous outburst of the star in 1945-47 strong absorption bands of titanium-oxide (TiO) suddenly appeared in its optical spectrum, together with many low excitation energy lines, not previously observed. These absorption lines, normally observed in M-type supergiants, were strongly blue-shifted, signaling the ejection of a cool circumstellar gas shell. In July 2000 we observed the formation of new TiO bands during a strong V-brightness decrease by $\sim 1^{\rm m}.4$ (*Fig. 1*). Our synthetic spectrum calculations show that $T_{\rm eff}$ decreased by at least 3000 K, from 7250 K to $\simeq$4250 K, and the spectrum became comparable to the early M-type supergiants μ Cep and Betelgeuse. The TiO bands reveal the formation of a cool circumstellar gas shell with T<4000 K due to supersonic expansion of the photosphere and upper atmosphere. We observe a shell expansion velocity of $v_{\rm exp}$=35$\pm$2 km s^{-1} from the TiO bands. From the synthetic spectrum fits to these bands we compute an exceptionally large mass-loss rate of $\dot{M}\simeq 5.4\times10^{-2}$ M$_\odot$ yr^{-1}, comparable to the values estimated for the notorious outbursts of η Carinae (Lobel et al. 2002, 2003b).

2. Recent Continuous Spectroscopic Monitoring

Over the past three years since the outburst we observed an unusually strong inverse P Cygni profile in Balmer Hα, indicating a new collapse of ρ Cas's extended upper atmosphere. Over the past year we observe how the Hα line transformed from a prominent inverse P Cygni profile into

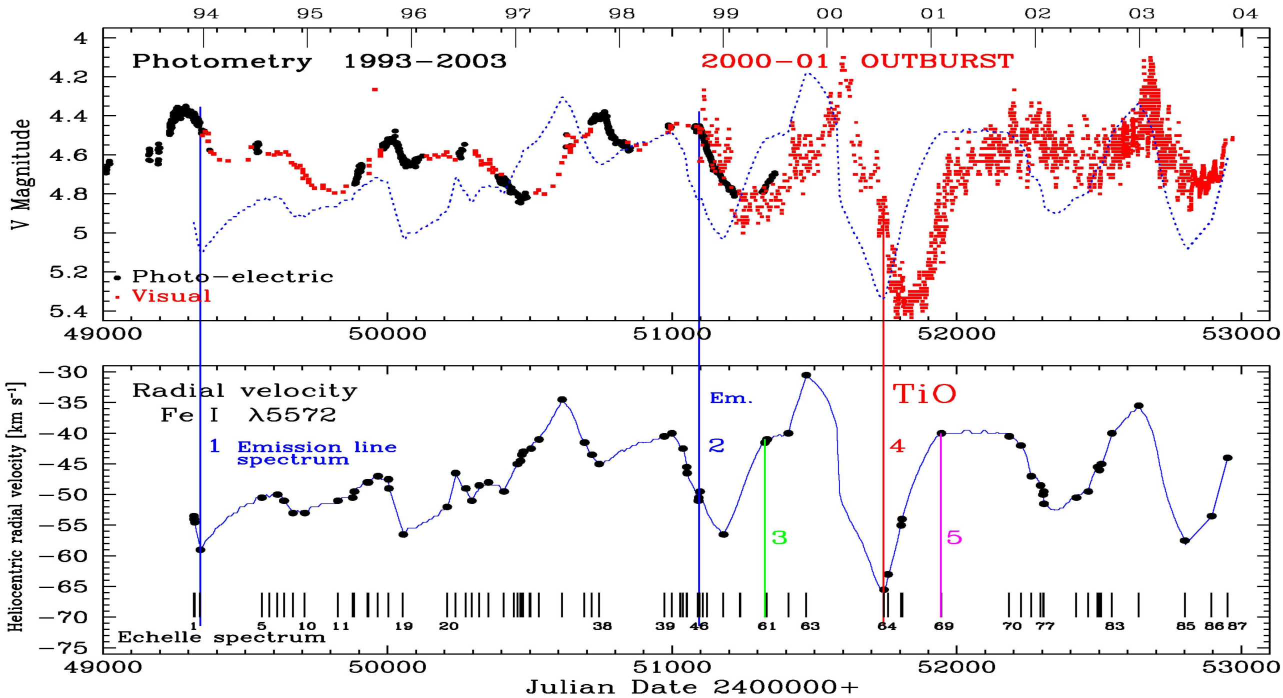

Figure 1. Visual brightness changes observed in ρ Cas between 1993 and 2003 (upper panel) are compared to radial velocity changes (lower panel) observed from an unblended photospheric absorption line of Fe I *λ5572. Fast atmospheric expansion in late 1999 and early 2000 precedes the deep visual outburst minimum of summer 2000. Continuous high-resolution spectroscopic observations are marked with short vertical lines in the lower panel. A prominent emission line spectrum is observed during phases of fast atmospheric expansion in Dec. '93 and Oct. '98 (labeled 1 and 2), and in Jan. '02 and July '04 (see Fig. 2).*

a P Cygni profile (*Fig. 3*). The P Cygni line shape of Hα is very remarkable because it was not clearly observed during the 2000 brightness minimum. It indicates a new strong expansion of the upper atmosphere. We currently measure expansion velocities up to 120 km s^{-1} for the Hα atmosphere. Our very recent high-resolution spectroscopic observations of April 2004 indicate that the P Cygni line shape further strengthens, resulting in a new and exceptional variability phase of enhanced mass-loss. This spectral evolution is expected since we observe that the radial velocity curve of the absorption portion of Hα is at least twice longer than the (quasi-) period of photospheric absorption lines with P∼300-500 d (Lobel 2001b).

Figure 5 shows dynamic spectra of Hα and Fe I λ5572 observed between 1993 and late 2003. The white spots in Hα are emission above the stellar continuum level. The radial velocity curves of the Hα absorption core and the photospheric Fe I lines (*white dashed lines*) reveal a velocity stratified dynamic atmosphere. Notice the large blueshift of the Fe I lines during the outburst of mid 2000. The outburst is preceded by enhanced emission in the short wavelength wing of Hα, while the Fe I line shifts far redward. A strong collapse of the upper Hα atmosphere and the lower photosphere precedes the outburst event during the pre-outburst cycle of 1999 (Lobel et al. 2003c) (see *Fig. 1*).

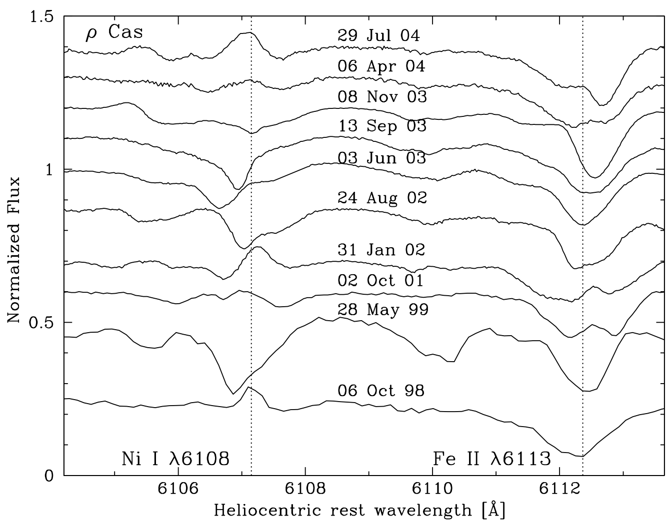

Figure 2. Spectral changes observed in ρ Cas since mid 2004 reveal prominent atomic emission lines in the optical and near-IR spectrum. The Ni I *λ6108 line transforms from absorption into emission above the level of the stellar continuum during phases of fast atmospheric expansion in Fig. 1. Similar emission features appear in the central core of photospheric absorption lines with small lower excitation energy as Fe* II *λ6113, causing recurrent double (or split) absorption line cores.*

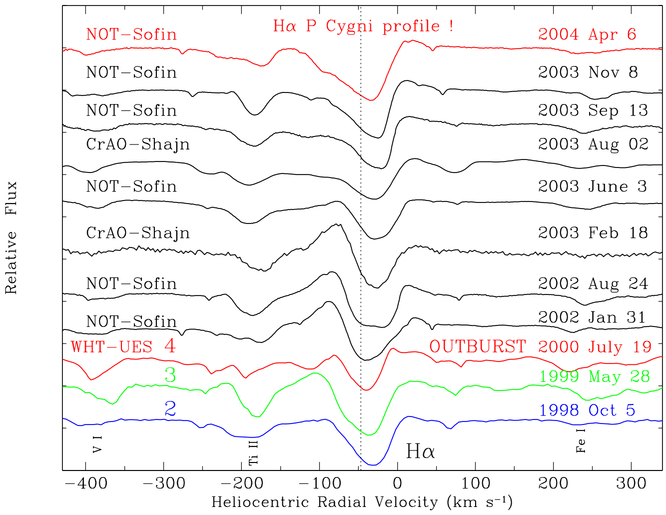

Figure 3. Line profile changes of Hα in ρ Cas reveal that following the outburst event of 2000 the upper atmosphere collapsed over a period of ∼2.5 years producing a strong inverse P Cygni profile. Hα transformed into a P Cygni profile since mid 2003, presently showing highly supersonic atmospheric expansion comparable to the 2000 outburst. The vertical line is drawn at the stellar rest velocity of -47 km s^{-1}.

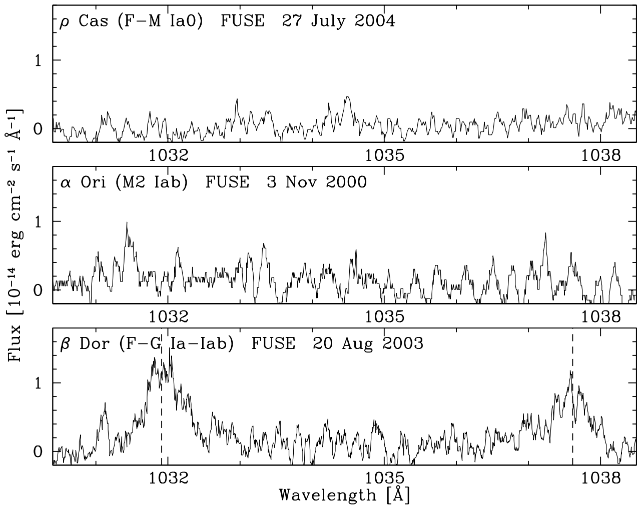

Figure 4. FUSE observations show that high-temperature emission lines of O VI *λ1032 & λ1037 are neither observed in yellow hypergiant ρ Cas (upper panel), nor in red supergiant α Ori (middle panel). The lines are however clearly observed in the smaller supergiant Cepheid variable β Dor (lower panel).*

3. Far-UV, Optical, and Near-IR Emission Lines

The optical and near-IR spectrum of ρ Cas (Ia0e) only sporadically reveals prominent emission lines. The emission lines are due to neutral and singly ionized atoms. In a spectrum of ρ Cas we observed on 29 July 2004, many exceptionally strong emission lines with low excitation potentials have re-appeared. The lines have only been observed in emission during previous phases of very fast atmospheric expansion in late '93 (Lobel 1997), fall 1998, and early 2002. Figure 2 shows how the Ni I λ6108 line transformed from absorption into emission with the fast expansion of the upper atmosphere over the past half year. The line appears however in absorption during pulsation phases of photospheric collapse when $T_{\rm eff}$ increases. The formation of these rare emission lines therefore appears linked with an excitation phenomenon that can result from supersonic wind expansion during exceptional variability phases. A possible interpretation is that the emission spectrum is excited by a propagating circumstellar shock wave passing through the line formation region in the extended outer atmosphere (de Jager et al. 1997).

The optical and near-IR emission line spectrum of ρ Cas is currently under investigation together with the far-UV spectrum observed with *FUSE* on 27 July '04. The *FUSE* spectrum does not reveal the high temperature emission lines of O VI λ1032 & λ1037 (*Fig 4*), or the C III λ977 line. Our far-UV observations also demonstrate that there is no evidence of a faint hot (e.g. white dwarf) companion star in ρ Cas, also ruled out by our long-term radial velocity and light curve monitoring. However, we clearly observe these warm transition region plasma emission lines in the classical Cepheid variable β Dor (F-G Iab-Ia). Its smaller radius of R_*=64 R$_\odot$, compared to ρ Cas (R_*≃400-500 R$_\odot$ with log(g)=0.5-1.0), signals that the larger average atmospheric gravity acceleration is an important stellar parameter to sustain high-temperature plasmas in the outer atmosphere of less luminous (pulsating) supergiants. This is supported by the observation that transition region plamsa emission lines are also absent in red supergiant α Ori with R_*=700 R$_\odot$ and log(g)=−0.5.

4. Conclusions

We present new recent spectral observations of the yellow hypergiant ρ Cas that reveal enhanced dynamic activity of its pulsating atmosphere during the past three years after the outburst event of 2000. A strong inverse Balmer Hα P Cygni profile that transformed into a P Cygni profile, currently signals supersonic wind expansion up to 120 km s^{-1} of the upper atmosphere with enhanced mass-loss. During the fast atmospheric expansion we observe the return of a prominent neutral and singly ionized atomic emission line spectrum in the optical and near-IR. Very recent observations of the far-UV spectrum with *FUSE* demonstrate the absence of high ion emission lines due to warm transition region plasma in the extended dynamic atmosphere of the hypergiant.

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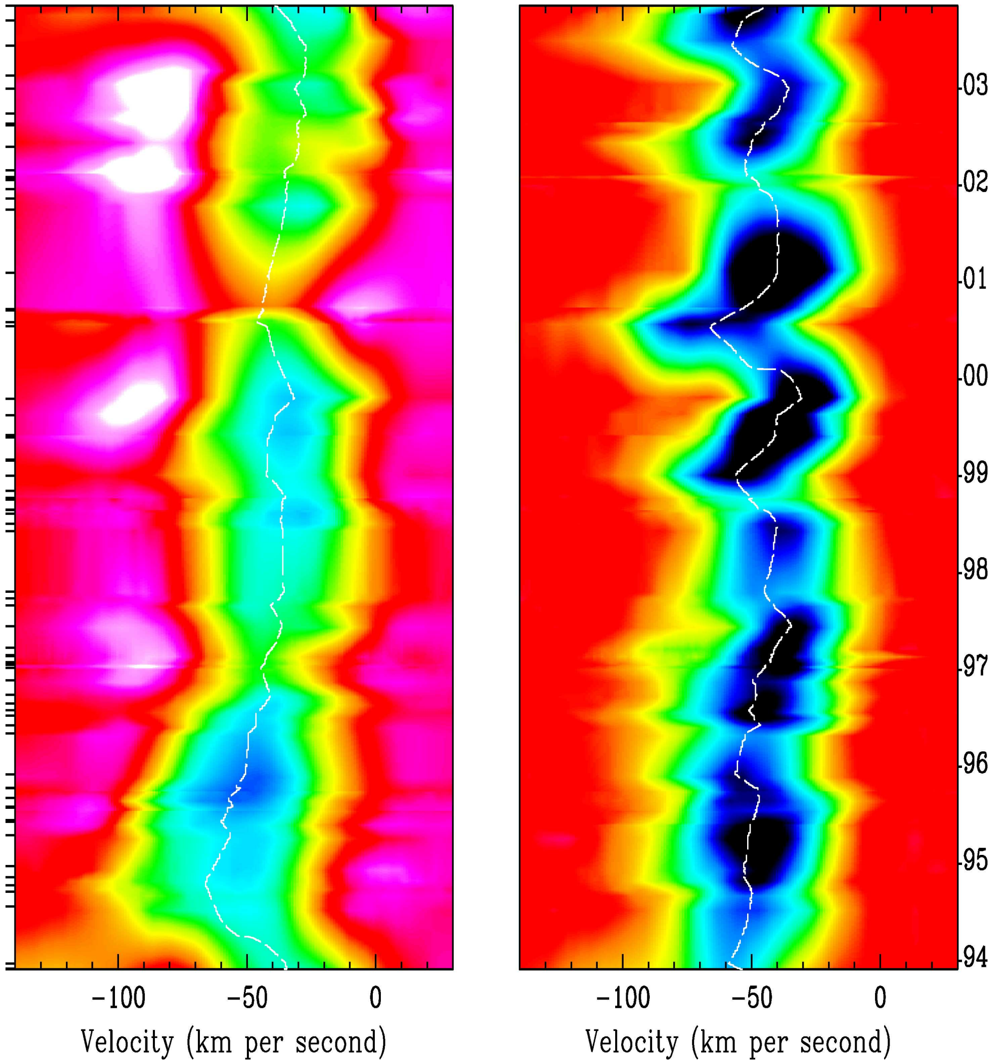

Figure 5. Dynamic spectra of Hα (panel left) and Fe I *λ5572 (panel right). The line profiles are linearly interpolated between consecutive observation nights in the past decade, marked by the left-hand tickmarks. Notice the strong blue-shift of the Fe* I *line during the outburst of mid 2000. The outburst is preceded by very strong emission (white spots) in the short-wavelength wing of Hα, while the absorption core extends longward, and the photospheric Fe* I *line strongly red-shifts. A strong collapse of the upper and lower atmosphere precedes the outburst. Fast expansion of the upper Hα atmosphere is also observed over the past year.*

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