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THE MYSTERIOUS Of?p CLASS AND THE MAGNETIC O-STAR θ^1 Ori C: CONFRONTING OBSERVATIONS

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RESUMEN

En años recientes, las estrellas de la categoría Of?p han revelado una multitud de fenómenos peculiares: perfiles de líneas variables, cambios fotométricos y exceso de luminosidad en rayos X son solamente algunas de sus características. Aquí repasamos sus propiedades físicas, para facilitar comparaciones entre los miembros galácticos de esta clase. Dado que uno de ellos se ha propuesto como semejante al rotador magnético oblicuo θ^1 Ori C, aunque con un período más largo, este último objeto está también incluido en nuestro estudio, para ilustrar sus similitudes y diferencias con la categoría Of?p.

ABSTRACT

In recent years, the stars of the Of?p category have revealed a wealth of peculiar phenomena: varying line profiles, photometric changes, and X-ray overluminosity are only a few of their characteristics. Here we review their physical properties to facilitate comparisons among the Galactic members of this class. As one of them has been proposed to resemble the magnetic oblique rotator θ^1 Ori C, though with a longer period, this latter object is also included in our study to illuminate its similarities and differences with the Of?p category.

Key Words: stars: early-type — stars: individual (HD 108, HD 148937, HD 191612, $\boldsymbol{\theta^1}$ Ori C) — stars: variables: other

1. INTRODUCTION

In astronomy, the study of peculiar objects often provides crucial information. Indeed, a rare phenomenon could be linked to short-lived phases in the evolution of stars or galaxies. It might thus represent a 'missing link' in our understanding of the Universe, therefore deserving an in-depth analysis.

Though rare, O-type stars are nevertheless important as they are the main sources of ionizing radiation, mechanical energy, and certain chemical elements in galaxies. However, their lifetimes are short (a few million years) and their rapid evolutionary phases are thus very difficult to study. To better understand these hot, massive objects, it is thus important to probe the properties of the most peculiar ones, such as the Of?p stars.

The Of?p category was defined by Walborn (1972, 1973) to classify stellar spectra displaying certain peculiarities, notably strong C III emission lines around 4650 Å (more details on classification criteria below). At first, only two stars belonged to this category, HD 108 and HD 148937, but a third one was soon added, HD 191612 (Walborn 1973). A few others have now been identified in the Magellanic Clouds (Heydari-Malayeri & Melnick 1992; Walborn et al. 2000; Massey & Duffy 2001; Evans et al. 2004). In recent years, these peculiar objects attracted quite a lot of attention because of the discovery of recurrent line-profile variations and X-ray overluminosities. A magnetic field was even reported for HD 191612, making it the second O-type star with a detected magnetic signature – the first one being θ^1 Ori C (Donati et al. 2002, 2006).

The aim of this short review is to summarize the properties of the Of?p stars, in the visible, UV, and X-ray domains, and to compare them to those of θ^1 Ori C, a known magnetic oblique rotator. This paper is organized as follows. § 2 describes the main properties derived from the UV/visible spectra of these stars, § 3 presents their photometric character-

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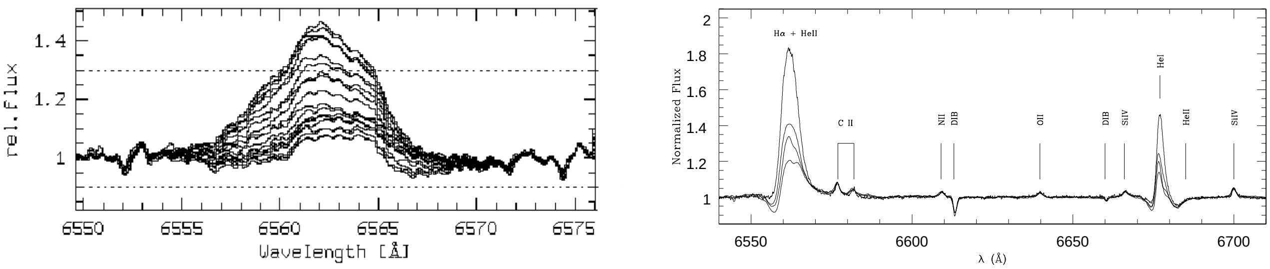


Fig. 1. Variations over the 15d period of the spectra of θ^1 Ori C (left, figure from Stahl et al. 1996) and evolution of the red spectrum of HD 108 between 1997 and 2003 (right, figure from Nazé et al. 2004).

istics, § 4 describes their observations in the X-ray domain, and § 5 gives our conclusions.

2. VISIBLE AND UV SPECTRUM

The study of O-type stars has long focused on the UV/visible spectra of these objects. Indeed, a wealth of information can be derived from them. To cite only a few: lines varying in position indicate binarity; relative line strengths indicate temperature; and emission-line profile variations relate to peculiar phenomena such as transient wind inhomogeneities, wind-wind collisions, or a disk confined by an oblique magnetic field. We present here the properties derived from the spectra of the Of?p stars and of θ^1 Ori C.

2.1. *Spectral Type*

Though θ^1 Ori C is often studied, its spectral classification is still under debate. It is generally considered to be O7 V (Stahl et al. 2008), but Walborn (1981) found a changing spectral type, which remains to be confirmed. In the context of this review, it is important to note the absence of strong C III λ 4650 in emission, which is one of the main characteristics defining Of?p stars.

The f?p designation should only be added when several spectral criteria are fulfilled. The most important one is of course the presence of a strong C III λ 4650 emission, i.e. of an intensity comparable to that of the neighboring N III lines. Additional features are common amongst Galactic Of?p stars: composite profiles for the Balmer hydrogen lines, with a narrow P Cygni/emission component superimposed on a broad (photospheric) absorption; P Cygni He I profile or asymmetric He I lines, with the red wing being steeper than the blue one; other peculiarities such as weak Si IV $\lambda\lambda$ 1393,1402 wind profiles unlike for Of supergiants, and, in some cases, the Si III $\lambda\lambda$ 4552,4568,4575 triplet in emission.

Comparing the He I to He II absorption lines, HD 148937 appears rather early, with a type O5.5-6f?p (Nazé et al. 2008), but the cases of HD 108 and HD 191612 seem more complex. In fact, the spectral types of these two stars are not constant: using the classical He I-He II indicators, they alternate between O4 and O8.5 for HD 108 (Nazé, Vreux, & Rauw 2001; Nazé et al. 2004), or O6.5 and O8 for HD 191612 (Howarth et al. 2007). As the C III λ 4650 emission is only present when these stars appear very early, the f?p designation is only added in this case, whereas the fp classification is sufficient when the spectral type is the latest[4].

2.2. *Line Profile Variability*

Hints at spectral changes in θ^1 Ori C were already reported by Conti (1972). The variability was further studied by Walborn (1981); Stahl et al. (1993); Walborn & Nichols (1994); Stahl et al. (1996, 2008). The largest variations are observed for the Balmer hydrogen and He II λ 4686 lines (Figure 1). However, the equivalent widths (EWs) of other lines, e.g. the photospheric lines of He I λ 4471, He II λ 4542, O III λ 5592, C IV λ 5801, appear to change in harmony with those of H and He II λ 4686, though with a smaller amplitude (15% change vs 100%) and with an opposite behaviour (maximum *absorption* when maximum *emission* is seen for H lines). Clear line profile variability was also found in the UV range for the Si IV $\lambda\lambda$ 1393,1402, C IV $\lambda\lambda$ 1548,1550 O V λ 1371 N IV λ 1718 lines, which display a maximum absorption when the H lines present a maximum emission (Walborn & Nichols 1994; Stahl et al. 1996). In addition, Walborn (1981) mentioned variations of the He I λ 4471/He II λ 4542 ratio, but this was not observed in subsequent studies (see e.g. Stahl et al. 1996, 2008).

[4]It is interesting to note an additional peculiarity when the spectral type is the latest: strong He II λ 4686 emission without the Si IV absorption typical of supergiants.

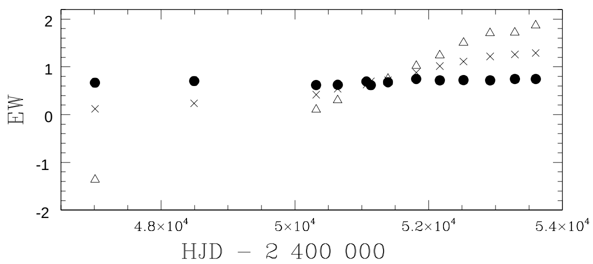


Fig. 2. Evolution of the equivalent widths of He I λ 4471 (crosses), He II λ 4542 (filled circles), and Hβ (open triangles) in the spectrum of HD 108 (figure from Nazé et al. 2006).

Among the Of?p stars, HD 108 has been the most studied, but conflicting results about its nature were reported: a short-period binary (Hutchings 1975; Aslanov & Barannikov 1989, the system having even survived a supernova event according to Bekenstein 1976); a single star experiencing wind variability and/or harboring a disc and jets (Vreux & Conti 1979; Underhill 1994); or a long-period (a few years) binary (Barannikov 1999)... To attempt to resolve the confusing situation, a 30-year spectroscopic campaign was undertaken at the Haute-Provence Observatory (Nazé et al. 2001). A detailed analysis of the data allowed most of the older models to be discarded and rather unveiled a peculiar phenomemon: dramatic line-profile variations on a timescale of decades (Figures 1 and 2; for the first hints of the phenomenon see also Andrillat et al. 1973). The Balmer hydrogen and He I lines change from strong P Cygni profiles to pure absorptions with asymmetric profiles. A few other emission lines were also found to be strongly variable (C III λ 4650, He II λ 4686).

Walborn et al. (2003) investigated another Of?p star, HD 191612, and discovered similar line profile variations. The changes apparently come from a varying narrow emission, slightly redshifted, superimposed on the 'normal' stellar lines. It should, however, be noted that not all lines are varying: He II λ 4200,4542, O III λ 5592, C III λ 5696, C IV λ 5812,... (all most probably of photospheric origin) appear relatively constant in strength (Nazé et al. 2001; Howarth et al. 2007). Therefore, since variability affects He I λ 4471 but not He II λ 4542, apparent spectral-type variations, measured from the He I/He II ratio, are detected, as noted above. Note that these changes have a long-term character, but small-scale, short-term variations are also observed for HD 191612 as well as HD 108 (Howarth et al. 2007; Nazé et al. 2008). In the remainder of the paper, we define the 'quiescent' state as the time when the contamination by excess emission is minimum, i.e. when the spectral type appears to be the latest.

Only little was known about HD 148937 until recently, when we undertook a spectroscopic campaign with the SMARTS program at the CTIO 1.5 m telescope. This monitoring revealed low-level variability in the Balmer and He II λ 4686 lines, but constancy for He I, C III λ 4650, and other lines (Nazé et al. 2008). Note that if this variability were similar in nature to that of HD 108 and HD 191612, though with a much lower intensity, we would expect no detectable variations of the He I and C III, as the hydrogen changes are the largest of all lines for these stars.

Because of the lack of high-quality data, the UV spectrum of the Of?p stars was only little investigated up to now – though the few IUE data available, shown in Figure 1 of Walborn et al. (2003), were of course used for model atmosphere fits (see § 2.4). The only significant result is the lack of strong variability between the two IUE spectra corresponding to the two extreme states of HD 191612 (data unfortunately taken with two different spectral resolutions, see Howarth et al. 2007). However, since these stars are highly variable, one still needs to be cautious before drawing conclusions from such a limited dataset. Additional observations are thus needed to undertake an in-depth analysis, similar to what has been done for θ^1 Ori C.

2.2.1. *Periodicity*

The EW changes of θ^1 Ori C are recurrent with a very stable period of 15.424±0.001d (Figure 3, see also Stahl et al. 2008), while those of HD 191612 display a period of 537.6±0.4d (Walborn et al. 2004; Howarth et al. 2007). Comparing all the available data, the changes observed in HD 108 also appear repeatable, on a timescale of a few decades (approximately 50–60 years, see Nazé et al. 2001, 2006)[5]. Finally, the line profile variations of Hα in HD 148937 present a possible periodicity of 7.031±0.003d (Nazé et al. 2008).

2.3. *Binarity*

Long-term radial velocity changes, a typical signature of binary motion, were reported for θ^1 Ori C

[5]It has sometimes been suggested that, despite the numerous similarities between HD 191612 and HD 108, the former object was much closer in nature to θ^1 Ori C than to HD 108, based on the 'similar' values of their periods. However, it must be underlined that the period ratios are actually comparable, P(HD 191612)/P(HD 108) $\sim$ P(θ^1 Ori C)/P(HD 191612), indicating that no significant conclusion can be drawn from such 'numerology'.

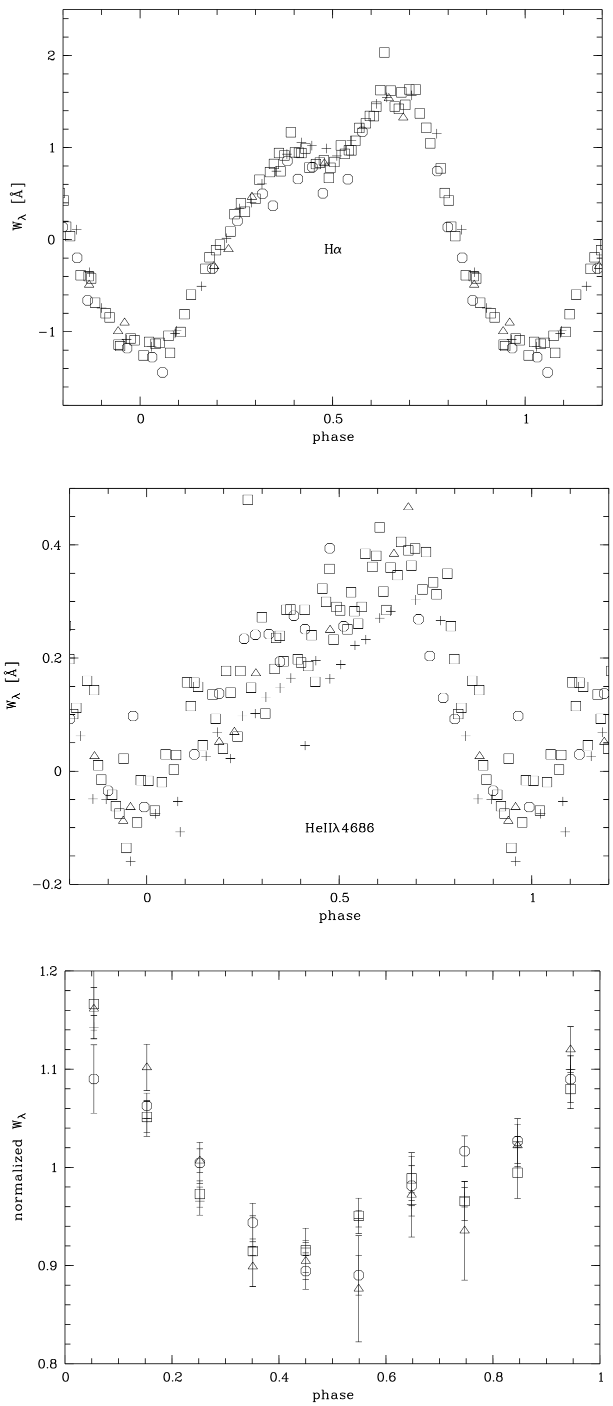


Fig. 3. Phase-locked variations in θ^1 Ori C of the equivalent width of Hα (top). Phase-locked variations in θ^1 Ori C of the equivalent width of He II λ 4686 (middle). On the bottom are shown the normalized and phase-averaged variations of the equivalent widths of He I λ 4471, He II λ 4542, O III λ 5592, and C IV λ 5801 (figures from Stahl et al. 1996).

by Stahl et al. (1993, see also summary in O'Dell 2001) and for HD 191612 by Nazé et al. (2007). Subsequent studies have provided more detailed orbital parameters. θ^1 Ori C is actually a visual binary and a first analysis of interferometric measurements yields a period of 10.9 yr, an eccentricity of 0.9, and a mass ratio of 0.45±0.15, suggesting the component spectral types to be O5.5 + O9.5, and the masses 34 + 15.5 $M_\odot$ (Kraus et al. 2007). These parameters were recently revised by Patience et al. (2008) who proposed a longer period (about 26 yrs) and a much smaller eccentricity (e = 0.16 ± 0.14), but the authors caution that the results are still preliminary since less than half the orbit has actually been observed. Radial velocities analyzed by Stahl et al. (2008) are consistent with the interferometric measurements, but do not permit to discriminate between both solutions. It should also be noted that rapid radial velocity changes are also detected but they seem uncorrelated with the 15d timescale of the line profile variability (Stahl et al. 2008). On the other hand, the radial velocity curve of HD 191612 shows that P=1542±14d, e=0.44±0.04, and M_2/M_1=0.48±0.04—the system thus probably contains an O8 + early-B star (30 + 15 $M_\odot$, Howarth et al. 2007).

The multiplicity of the other two Of?p objects is less clear. Though HD 108 was repeatedly suggested to be a binary in the past (Hutchings 1975; Aslanov & Barannikov 1989; Barannikov 1999), recent monitoring could discard the proposed solutions and all periods from a few days to a few years (Nazé et al. 2001). However, radial-velocity changes are detected for HD 108 (between −55 and −85 km s^{-1}, Nazé 2004; Nazé et al. 2006), and a very long-term binary cannot be excluded. HD 148937 displays no radial-velocity changes of amplitude larger than 10 km s^{-1} on short or long timescales (Conti, Garmany, & Hutchings 1977; Garmany, Conti, & Massey 1980; Nazé et al. 2008), but low-amplitude variations or very long-term changes are not excluded by the available data.

2.4. *Physical Parameters*

The spectrum of θ^1 Ori C was modeled in detail by Simón-Díaz et al. (2006) and Kraus et al. (2007); their results are reproduced in Table 1, with only one modification. In fact, the distance to the Orion Nebula was recently revised by Menten et al. (2007) to 414 pc (instead of the usual 450 pc, used notably by Simón-Díaz et al. 2006, or 434 pc of Kraus et al. 2007). The luminosity of θ^1 Ori C appearing in Table 1 was thus changed accordingly, as well as the

TABLE 1

PHYSICAL PARAMETERS OF θ^1 Ori C AND THE Of?p STARS

Star	$T_{\rm eff}$ (kK)	$\log\left(\frac{L}{L_\odot}\right)$	$\log(g)$	$\frac{R}{R_\odot}$	$v\,\sin(i)$ (km s^{-1})	Age (Myr)	$\frac{M}{M_\odot}$	References
θ^1 Ori C	39±1	5.13±0.13	4.1±0.1	8.1±1.3	24±3	0–2[a]	~ 30[a]	1
	39.9+31.9	5.31+4.58					34.0+15.5?[b]	2
HD 108	37±2	5.40±0.10	3.75±0.10	12.3±2.1	$\gtrsim 40$	2–4[a]	$\sim$35[a]	3
HD 148937	41±2	5.75±0.10	4.0±0.1	15.0±2.5	$\gtrsim 45$	2–4[a]	$\sim$55[a]	4
HD 191612	35±1	5.4	3.5±0.1	14.5	$\gtrsim 45$	2–4[a]	30+15?[b]/$\sim$ 35[a]	5

[a]Estimated from the position of the star in the HR diagram.

[b]Estimated from the orbital solution.

1. Simón-Díaz et al. (2006); this work. 2. Kraus et al. (2007); this work. 3. this work. 4. Nazé et al. (2008); this work. 5. Howarth et al. (2007); this work.

stellar radius, assuming the effective temperature is not changed, which is a fair approximation.

We estimated the projected rotational velocity of the Of?p objects by applying the Fourier method (see Simón-Díaz & Herrero 2007, and references therein) to uncontaminated, 'photospheric' lines (e.g. C IV λ 5812 and O III λ 5592). This method was also the one chosen by Simón-Díaz et al. (2006), thus enabling a direct comparison between the stars. It might be noted that these new values are lower than previous estimates because the Fourier method can disentangle the different contributions to the line broadening (Simón-Díaz & Herrero 2007). Model-atmosphere fits further provided the effective temperatures, gravities, and luminosities of the Of?p stars in the quiescent state (Howarth et al. 2007 for HD 191612, Nazé et al. 2008 for HD 148937, and this work for HD 108, see also Figure 4). The results are reported in Table 1. The best-fit gravity values clearly suggest that these stars are not supergiants, as was once proposed, but giants or main-sequence objects.

Figure 5 presents the positions of the stars in the HR diagram: two stars are close together, suggesting that they share similar properties, whereas HD 148937 appears clearly more massive and more luminous and θ^1 Ori C appears only slightly less massive and less luminous. Note that for the luminosity estimates, the distances to the Of?p stars are based on their supposed membership in OB associations (2.51 kpc, Cas OB5 for HD 108; 2.29 kpc, Cyg OB3 for HD 191612; and 1.38 kpc, Ara OB1a for HD 148937, see Humphreys 1978), which may be uncertain.

The masses were estimated by several methods: orbital solutions for binary objects, model-atmosphere fits ($M_{\rm spec} = gR^2/G$), and positions in the HR diagram compared to predictions of evolutionary models. The values derived by the first and last methods are listed in Table 1, with a superscript indicating the method used. The different determinations generally coincide very closely for a given star, except for HD 148937 where the HR-diagram mass is at 1σ from the spectroscopic mass ($82\pm33\,M_\odot$), but still within the error bar.

The ages of the stars were estimated by comparing their positions in the HR diagram to theoretical isochrones, which yields 2–4 Myr for the Of?p objects and $\sim$ 1 Myr for θ^1 Ori C. The ages of the associations to which the stars belong generally provide a more accurate estimate. For our objects, this method yields $<$ 1–2 Myr for θ^1 Ori C (Hillenbrand 1997), 2–5 Myr for HD 191612 (Massey, Johnson, & DeGioia-Eastwood 1995), and 0–3 Myr for HD 148937 (Vázquez & Feinstein 1992). θ^1 Ori C seems to be the youngest system of the sample, in agreement with its location in the Orion Nebula Cluster, but the uncertainties on the ages of the Of?p objects make a more detailed comparison difficult.

2.4.1. *Evolutionary Status: Peculiar Abundances and Circumstellar Material*

Model atmosphere fits are also able to reveal the abudance pattern. For HD 108 and HD 148937, they unveil a clear overabundance of nitrogen: for HD 108, N/H is 6×10^{-4}, i.e. a value about 9 times solar (this work) while it is 3×10^{-4}, or about 4 times the solar value, for HD 148937 (Nazé et al. 2008). A comparison of line strengths in the spectra of the Of?p stars suggests a similar overabundance for HD 191612. This enrichment, together with the presence of common spectral features, points towards

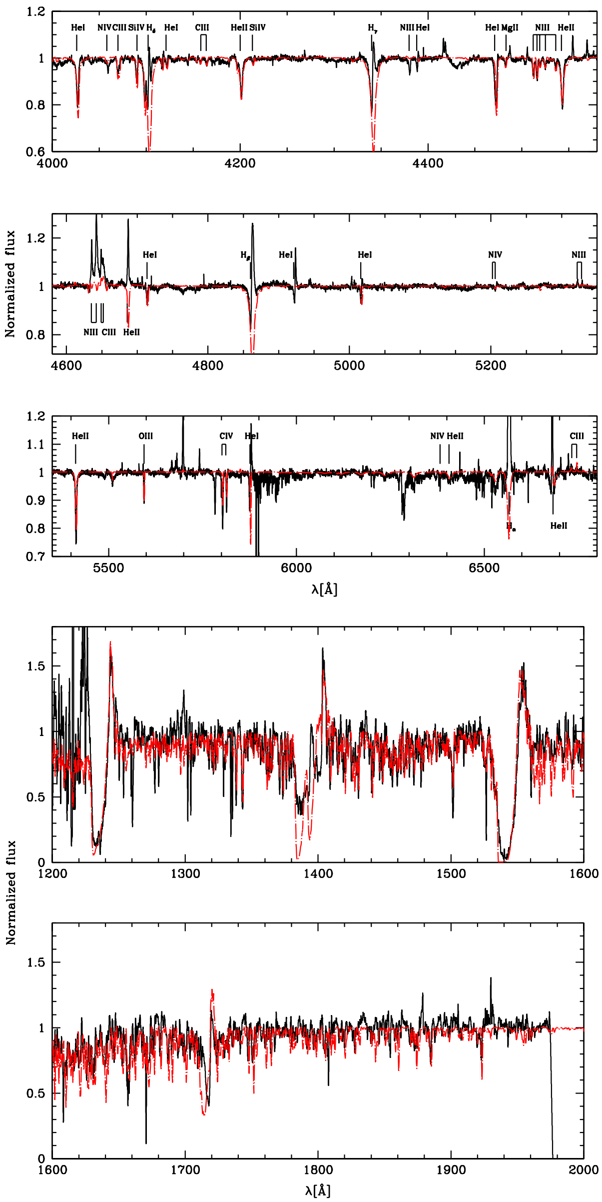


Fig. 4. Comparison of the optical and UV spectrum of HD 108 (solid black line) and the best fit CMFGEN model (dash-dot red line; see Table 1 for parameters. Note that the fit also yields $\dot{M} = 1-3\times10^{-7}\ M_\odot\ \mathrm{yr}^{-1}$ for a clumping factor f=0.01). The narrow emission components in the He I and H optical lines are not fitted and are most probably of circumstellar origin (disk?). This figure only appears in colors in the electronic version of the journal.

similarities between the Of?p stars and Ofpe/WN9 objects (Walborn et al. 2003), suggesting that these stars might be slightly evolved objects.

In this context, it is interesting to note that HD 148937 is surrounded by a circumstellar nebula:

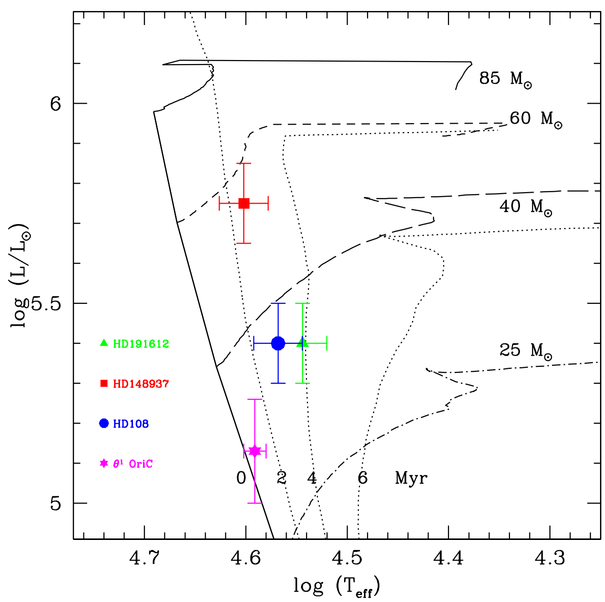


Fig. 5. HR diagram with Geneva isochrones and evolutionary tracks from Meynet & Maeder (2005).

the bipolar nebula NGC 6164-6165. The northwest lobe, NGC 6164, is receding while the southeast lobe, NGC 6165, is approaching; this suggests an expansion, with a projected velocity of 30 km s^{-1} (Leitherer & Chavarría-K. 1987). Moreover, the nebula displays anomalous chemical abundances, and it was therefore suggested to have been formed through an eruption of the Of?p central star (Leitherer & Chavarría-K. 1987; Dufour, Parker, & Henize 1988). Evidence of this process can be found in the similar nitrogen overabundances of the nebular and stellar data (factor of 4–5 compared to the solar value; Dufour et al. 1988; Nazé et al. 2008). It is possible that the lower amplitude of the line-profile variability for HD 148937 arises from a relaxation of the system following a Luminous-Blue-Variable-like eruption.

3. PHOTOMETRIC VARIABILITY

Hipparcos broad-band photometry of HD 191612 exhibits a clear modulation with a period of ∼538 d (Koen & Eyer 2002; Nazé 2004). The spectroscopic and photometric variations are clearly in phase: when the emission lines are weakest and the star displays an O8 spectral type, the star is fainter; when the emissions are maximum and the spectral type is earlier, then the star is brighter (Walborn et al. 2004).

Variable photometry was also reported for HD 108 (Barannikov 1999, 2007). In fact, the brightness of the star clearly decreased in recent years

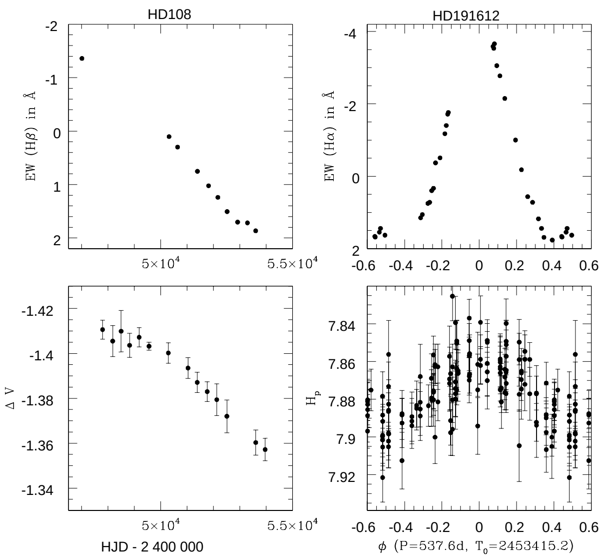


Fig. 6. Photometric and EW changes of HD 108 (left, data from Nazé et al. 2006 and Barannikov 2007) and HD 191612 (right, data from Hipparcos archives and Nazé et al. 2007). Negative EWs correspond to emission features.

(ΔV=0.06 mag). No significant color variation was found, but the declining luminosity clearly correlates with stronger He I absorptions and weaker H emission lines in the visible spectrum of the star: the photometric variability of HD 108 and HD 191612 thus appears very similar (Figure 6).

As HD 108, HD 148937 was included in the "New Catalogue of Suspected Variable Stars" (Kukarkin et al. 1981) but its variability status is actually not ascertained. On the one hand, short-term variability was observed by Balona (1992): the star dimmed by 0.01 mag over a few weeks. On the other hand, van Genderen et al. (1989) consider the star to have a constant luminosity in V, though with possible color changes ($\sim$0.002 mag); a larger dispersion of the magnitude might have been observed during some observing runs. The same authors further suggested that HD 148937 might have been bluer and brighter in the late eighties than in 1960. Finally, HD 148937 was classified as a possible candidate S Dor variable, but with only weak indications for that status (van Genderen 2001).

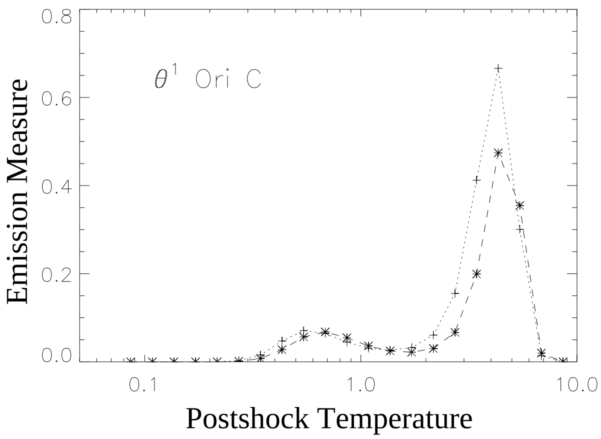
No thorough photometric variability analysis has been made for θ^1 Ori C. However, it is also included in the "New Catalogue of Suspected Variable Stars" (Kukarkin et al. 1981) and Hipparcos data display some (apparently) stochastic variability with an amplitude of about 0.14 mag (between 4.56 and 4.70 mag, Perryman & ESA 1997). Simón-Díaz et al. (2006) suggested that the 15d variability of the 'photospheric'-line EWs could be explained by dilution by a varying continuum. However, other scenarios have been proposed: excess absorption due to corotating clouds when the star is seen pole-on (Stahl et al. 1996), or excess emission due to infalling material when the star is seen equator-on (Smith & Fullerton 2005; Wade et al. 2006). Photometric changes linked to the 15d period thus remain to be identified.

4. X-RAY PROPERTIES

Several high-resolution X-ray spectra of θ^1 Ori C were obtained with the Chandra Observatory (Schulz et al. 2000; Gagné et al. 2005). These data revealed that θ^1 Ori C displays a very hard X-ray spectrum, with a clear overluminosity ($\log[L_X/L_{\rm BOL}]=-6.0$, to be compared with the 'canonical' value of -6.9 from Sana et al. 2006). The spectrum is mainly thermal in nature, with two components of temperatures, 0.7 keV and 2.5–3 keV (Gagné et al. 2005). The hottest plasma clearly dominates the spectrum (Figure 7). In addition, the X-ray lines appear very narrow (FWHM $\sim$600 km s^{-1}, i.e. much less than the wind terminal velocity), as expected for a magnetic oblique rotator model (Babel & Montmerle 1997; Gagné et al. 2005). Finally, the X-ray emission is not constant, but varies in phase with the H line emissions of the visible spectrum.

The XMM-*Newton* observations of Of?p stars detected large overluminosities ($\log[L_X/L_{\rm BOL}]$ = -6.0 to -6.2), but they also unveiled crucial differences from θ^1 Ori C (Nazé et al. 2004, 2007, 2008). First, the X-ray spectra of the Of?p objects are rather soft. In the best fits, two temperatures are found but the lower one (0.2–0.3 keV) clearly dominates (Figure 7). In fact, the component at higher temperature (1–3 keV) accounts for only 30% of the unabsorbed flux: it can thus not explain the overluminosity by itself. Second, the X-ray lines are rather broad (FWHM $\sim$1800 km s^{-1}, a value similar to the wind terminal velocity), as is found for 'normal' O-type stars.

An intriguing characteristic of HD 191612 must be noted: as for θ^1 Ori C, its X-ray flux decreased (by 40%) as the emission lines declined in the visible spectrum. However, since all observations were taken during the same 538d cycle, it is not yet known whether this variability is phase-locked and if so, with which period (the period of the binary, 1542d, or the period of the line profile variations, 538d).



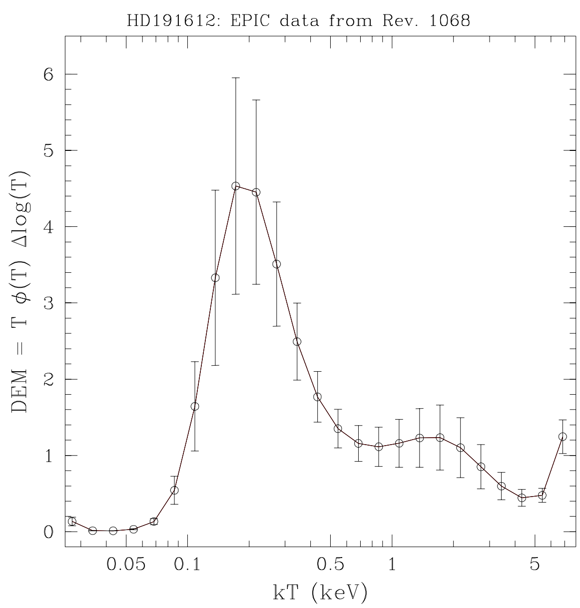


Fig. 7. Differential Emission Measure of θ^1 Ori C (top, from Zhekov & Palla 2007) and HD 191612 (bottom, from Nazé et al. 2007).

5. MAGNETIC OBSERVATIONS

Donati et al. (2002, 2006) reported the detection of magnetic fields in θ^1 Ori C and HD 191612, respectively, through the analysis of the Zeeman signature in several lines of the visible spectrum. With multiple observations of this signature throughout the 15d cycle, it clearly seems that θ^1 Ori C is indeed a magnetic oblique rotator as had been suggested before. In this model, the modulation observed in the visible and X-ray domains comes from the viewing angle of the magnetically confined disk, which changes with the stellar rotation, i.e. stronger emissions are detected when the disk is seen face-on (for a more detailed modeling see Smith & Fullerton 2005). Donati et al. (2006) then proposed HD 191612 to be an evolved version of θ^1 Ori C. In this case, the 538d timescale would be the rotation period of the star, which would have been braked as a result of the intense magnetic field. Using also spectropolarimetric data, Hubrig et al. (2008) recently reported the detection of a magnetic field for HD 148937. Additional spectropolarimetric measurements of HD 191612 and HD 148937 are now needed to check if the observed magnetic field follows the phase-locked evolution expected for magnetic oblique rotators.

6. SUMMARY AND CONCLUSIONS

The unusual Of?p stars and θ^1 Ori C share several similarities but display also intriguing differences (see Table 2).

In the visible domain, typical lines of O-type spectra, several being in emission or having P Cygni profiles, are observed for all stars, but the Of?p stars present a rare feature in addition: strong C III λ 4650 emission, the exact origin of which is still unknown. Spectral variability is detected for all objects, but the details vary from one case to another. The common characteristic is the presence of variations of the H and He II λ 4686 lines. The He I and C III lines also show large profile changes, but only for HD 108 and HD 191612; for θ^1 Ori C, photospheric lines also vary, but at a low level, which might be due to variations in the continuum level; and the observed variability of HD 148937 has the lowest intensity of all. These line-profile variations appear recurrent in each case, but with very different timescales: 7d for HD 148937, 15d for θ^1 Ori C, 538d for HD 191612, and 55 yr for HD 108. These periods are apparently not linked to orbital motion: the two known binaries (HD 191612 and θ^1 Ori C) present much longer orbital periods. However, the periods are related to changes seen in X-rays (for θ^1 Ori C and possibly HD 191612) or in broad-band photometry (for HD 191612 and HD 108). For the latter two objects, the spectral type appears earlier (due to filling in of the He I lines) when the brightness is greater and the emission lines stronger.

The physical parameters are also quite similar (Table 1): low projected rotational velocities, temperatures of about 40 kK, radii and gravities favoring a main-sequence or giant classification. However, the more massive HD 148937 is surrounded by a circumstellar nebula and all the Of?p objects display nitrogen enrichment in their spectra: these stars are thus likely slightly more evolved than θ^1 Ori C.

So far, magnetic fields have been detected in only a few O-type stars, among them θ^1 Ori C, HD 148937

TABLE 2

COMPARISON OF THE PROPERTIES OF θ^1 Ori C AND THE Of?p STARS

	θ^1 Ori C	HD 108	HD 148937	HD 191612
Sp. Type	O7V	O4f?p↔O8.5fp	O5.5–6f?p	O6.5f?pe↔O8fp
HI	var	var	var	var
He I	var	var	cst	var
He II λ 4686	var	var	var	var
C III λ 4650	not pr.	var	cst	var
Line prof. Period	15d	55yr	7d	538d
Binary Period	11–26yr	N?	N?	1542d
Magn. Field	Y	?	Y	Y
N enrichment	N	Y	Y	Y
Photometry	var?	L↓ when H↓	cst?	L↓ when H↓
X-ray excess	Y	Y	Y	Y
X-ray prop.	hard, narrow		soft, broad lines	

and HD 191612. Without further observations, however, we can not exclude the presence of magnetism in HD 108.

In the X-ray domain, the differences between the Of?p stars and θ^1 Ori C seem more pronounced. Although all present overluminosities compared to normal O-type stars, only θ^1 Ori C displays narrow lines and the hard spectrum expected for a magnetically confined wind.

In conclusion, HD 191612 (or the other Of?p stars) cannot 'simply' be identical to θ^1 Ori C since significant differences are clearly detected in their behaviors. On the other hand, their similarities should not be disregarded: for example, the unsual presence of a second peak in the differential emission measure of the Of?p high-energy spectrum could indicate the presence of a magnetically-confined wind, though it does not dominate the X-ray properties. It is therefore probable that the true nature of these objects is actually dual: something similar to θ^1 Ori C plus a yet unknown phenomenon, perhaps related to the age difference. In this context, understanding the exact origin of the C III emission in the Of?p objects might be a crucial step.

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