HD 148937: a multiwavelength study of the third Galactic member of the Of?p class[1]

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ABSTRACT

Three Galactic O-type stars belong to the rare class of Of?p objects: HD 108, HD 191612, and HD 148937. The first two stars show a wealth of phenomena, including magnetic fields and strong X-ray emission, light variability, and dramatic periodic spectral variability. We present here the first detailed optical and X-ray study of the third Galactic Of?p star, HD 148937. Spectroscopic monitoring has revealed low-level variability in the Balmer and He II λ 4686 lines, but constancy at He I and C III λ 4650. The Hα line exhibits profile variations at a possible periodicity of ∼7d. Model atmosphere fits yield $T_{eff} = 41000 \pm 2000$K, $\log(g) = 4.0 \pm 0.1$, $\dot{M}_{sph} \lesssim 10^{-7} M_{\odot}\,yr^{-1}$ and a surabondance of nitrogen by a factor of four. At X-ray wavelengths, HD 148937 resembles HD 108 and HD 191612 in having a thermal spectrum dominated by a relatively cool component (kT=0.2keV), broad lines (≥1700km s^{-1}), and an order-of-magnitude overluminosity compared to normal O stars ($\log[L_X^{unabs}/L_{BOL}] \sim -6$).

Subject headings: stars: individual: HD 148937 – stars: early-type – X-rays: stars – X-rays: individual: HD 148937

1. Introduction

The Of?p category was defined by Walborn (1972) to gather peculiar stars displaying strong C III emission lines around 4650 Å, i.e. of an intensity comparable to that of the neighbouring N III lines. Three stars of our Galaxy belong to this class: HD 108, HD 191612, and HD 148937. A few others have now been identified in the Magellanic Clouds (Heydari-Malayeri & Melnick 1992; Walborn et al. 2000; Massey & Duffy 2001).

In recent years, these peculiar objects have attracted quite a lot of attention. In 2001, it was discovered that HD 108 presents dramatic line-profile variations of its C III, He I and Hydrogen lines (Nazé et al. 2001). These variations seemed recurrent with a timescale of approximately 50–60 years (see also Nazé et al. 2006). Walborn et al. (2003) then reported a similar phenomenon for the spectrum of HD 191612. However, the period was much shorter (only 538d) and appeared correlated with photometric changes (Walborn et al. 2004). A magnetic field was subsequently identified for this star (Donati et al. 2006), with the 538 d proposed to be linked to the rotation period. In this scenario, HD 191612 would be an oblique magnetic rotator, a somewhat evolved version of θ^1 Ori C (Donati et al. 2006). The measured period would correspond to the rotational period of the star, which has been slowed down by the magnetic field, and larger emissions would be detected when the magnetically-confined disk is seen face-on while there are reduced or no contamination by emission when the disk is seen edge-on.

However, the analysis of a dedicated XMM-*Newton* observing campaign did not reveal the dominant signature of a magnetically-confined X-ray emitting plasma: apart from a clear over-luminosity, both HD 108 and HD 191612 display characteristics typical of massive O-type stars (broad lines, low kT; see Nazé et al. 2004, 2007). Optical observations have further shown HD 191612 to be a binary, though with a different period (1542d, see Howarth et al. 2007). A magnetically-confined disk therefore appears insufficient to explain the full behaviour of those Of?p stars; an additional source of relatively soft X-rays is needed but its origin is still unknown (is it somehow related to binarity, like e.g. colliding wind emission, or is it a more exotic phenomenon?)

In comparison, only little is known about HD 148937, and no thorough study of the star has been undertaken until now. The most interesting information comes from its environment: the star is surrounded by a bipolar nebula, NGC 6164-6165, that displays a very symmetrical geometry. Due to its anomalous chemical abundances, this nebula is thought to have formed through an eruption of the star, maybe similar to that of η Carinae in the nineteenth century (Dufour et al. 1988), making HD 148937 a candidate Luminous Blue Variable object.

The aim of our study is to assess the properties of HD 148937, in the visible and X-ray domains, and to compare it to the other two galactic Of?p stars. This paper is organized as follows. Section 2 describes the observations while Sections 3, 4 and 5 present the results of the available photometric datasets, the dedicated optical spectroscopic campaign and the XMM-*Newton* observations, respectively. Section 6 gives our conclusions.

2. Observations and Data Reduction

2.1. Visible domain

Low-resolution spectroscopy of HD 148937 was gathered between 2003 and 2006 via SMARTS (Small and Moderate Aperture Research Telescope System) at the CTIO 1.5m telescope equipped with the RC spectrograph. For each observation, three exposures of one to two minutes were combined, and the final signal-to-noise ratio (S/N) in the continuum was generally about 100. Three different gratings and/or settings were used: one covering the range 5650–6800 Å with a resolution of 2.8Å the second 4000–4900 Å with a resolution of 2.0Å, and the last 4065–4700 Å with a resolution of 1.6Å. All the reductions were performed using the IRAF and MIDAS software. The normalization was done by fitting polynomials through carefully chosen continuum win-

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dows. The observations were relatively evenly distributed between the months of February and October. During the 4 years of the observing campaign, at least one blue+red spectrogram pair was taken each month of this visibility window. In total, we collected 53 red spectra and 56 blue ones.

Additional high-resolution spectra covering the whole optical range (3750–9200 Å) were collected using the Fiber-Fed Extended Range Optical Spectrograph (FEROS), an echelle instrument mounted at the MPG/ESO 2.2-m telescope at La Silla. The resolution of FEROS is 0.1 Å at 4800 Å (thus R=48000); the exposure time was 15 min, leading to a signal-to-noise ratio of minimum 300. The spectra were all taken during the month of May (2003 May 24 and 25, 2004 May 6 and 2005 May 19). These data were reduced by the observers, E. Gosset and H. Sana, using an improved version of the FEROS context (Sana et al. 2003) working under the MIDAS environment. After correcting for the blaze using flat fields, the different orders were normalized individually using polynomials of order 4–6.

Other high-resolution observations can be found in the archives. A first one was taken with FEROS on 2005 June 26 and was kindly made available to us by the PI, J.-C. Bouret (S/N=200). Another one, taken on 1995 April 15 with University College London Echelle Spectrograph (UCLES), was found in the AAT archive. It consists of three exposures of 3–5min with S/N of about 140 that provide a spectrum covering the wavelength range from 3800 to 7400 Å with a resolving power of 36000. The reduction of this observation was done in a classical way using the IRAF and MIDAS software. Finally, the star was also observed on 2002 February 27 with the Ultraviolet and Visual Echelle Spectrograph (UVES), in the framework of the UVES POP programme. The resolution was about 0.05Å, and the signal-to-noise ratio $\sim$250. The reduced and merged UVES spectrum was downloaded from the public ESO database[2]. Only a few selected regions were extracted from the UVES spectrum. All these spectra were corrected for the blaze using flat fields and then normalized using low-order polynomials.

[2]http://www.sc.eso.org/santiago/uvespop

2.2. X-ray range

On 2001 Feb. 25 (Rev. 0223, PI R. Smith), HD 148937 was observed twice consecutively with XMM-*Newton*, for a total exposure time of 30ks. The star is associated with sources J163352.4–480640 and J163352.3–480641 in the 1XMM catalog. We retrieved the two datasets from the XMM-*Newton* public archives, in order to perform a thorough analysis. For these observations, the three European Photon Imaging Cameras (EPICs) were operated in the standard, full-frame mode, except for the second pn dataset which was taken in the extended full frame mode. A medium filter was used to reject optical light. We processed these archival data with the Science Analysis System (SAS) software, version 7.0. After the pipeline chains (tasks EMPROC, EPPROC and RGSPROC), the data were filtered as recommended by the SAS team: for the EPIC MOS (Metal Oxide Semi-conductor) detectors, we kept single, double, triple and quadruple events (i.e. pattern between 0 and 12) that pass through the #XMMEA_EM filter; for the EPIC pn detector, only single and double events (i.e. pattern between 0 and 4) with flag=0 were considered. To check for contamination by low-energy protons, we have further examined the light curve at high energies (Pulse Invariant channel number>10000, E$\gtrsim$10 keV, and with pattern=0). No single, individual flare was detected during the observations but the background level was rather high and quite variable during the whole exposure. Further analysis was performed using the FTOOLS tasks and the XSPEC software v 11.2.0.

3. Photometry

HD 148937 was included in the "New Catalogue of Suspected Variable Stars", under the entry NSV 7808. In this catalogue, it presents a V magnitude between 6.71 and 6.81 mag. However, the variability status of this star is still under debate. Balona (1992) found a possible dimming of the star by about 0.01 mag over a few weeks time. Following van Genderen et al. (1989), the star rather presents a constant luminosity in V, although with a dispersion of 0.005 mag in April 1983, and possible small color variations ($\sim$0.002 mag). Comparing with older data, the same authors also noted that HD 148937 might have been bluer and brighter in the late eighties than in 1960. Finally, van Genderen (2001) considers HD 148937 as a possible candidate S Dor variable, but with only few indications for its S Dor status.

The three galactic Of?p stars were observed by the *Hipparcos* satellite[3]. We have downloaded the individual photometry measurements from the *Hipparcos* database, including the *Tycho* data in the B and V filters and the *Hipparcos* broad band filter H_p. After discarding the measurements with non-zero flags to get rid of possibly problematic data, we have analyzed the photometry of HD 148937 (=HIP 81100, see Fig. 1). The star displays a H_p magnitude varying between 6.79 and 6.83 mag, but the data are relatively sparse. Nevertheless, we have determined the reduced χ^2 when fitting the data by a constant luminosity, calculated the autocorrelation for each dataset, and performed a period search. No significant change or periodicity was detected: the variable/S Dor status of HD 148937 still awaits confirmation.

4. Visible spectroscopy

The full visible spectrum of HD 148937 is shown in Fig. 2. Compared to recent, quiescent spectra of HD 108, that of HD 148937 presents appreciably weaker absorption lines of N III$\lambda\lambda$4510-4534 and He II. The faint Si III, O II, and C II emission lines seen in HD 108 do not exist here, O IIλ4705 being rather in absorption. The two Si IV$\lambda\lambda$4088,4116 lines are however clearly in emission, whereas they were in absorption in the spectra of HD 108. We may also note the important strength of the He Iλ6678 emission line, compared to Hα, in the spectrum of HD 148937. In addition, no P Cygni profile is seen for the He I$\lambda\lambda$4471,4713 lines nor for the Hγ or Hβ lines (all are pure absorption). However, their profiles are not symmetric, with the red wing being much steeper than the blue one, indicating a possible contamination by some emission, most probably coming from the wind.

The spectral type of HD 148937 appears rather early. In the high-resolution spectra, a visual comparison of the He Iλ4471 with He IIλ4542 lines and of He Iλ4026 with He IIλ4200 favors a O6 spectral type (see Fig. 2 and Walborn & Fitzpatrick 2000). From the measurements of the equivalent widths (EW) of the former pair (see below), the high-resolution spectra again favors O6, whereas the low-resolution SMARTS data rather give O5.5, but close to the limit between the O5.5 and O6 types (see Fig. 3). The star has been previously classified as O6 (Mac Connell & Bidelman 1976; Penny et al. 1996; Garrisson et al. 1977), O6.5 (Walborn 1972) and O7 (Conti et al. 1977; Humphreys 1975). These variations, if real, may indicate a similar behaviour as seen in HD 108 and HD 191612. However, these older spectral type determinations were reported more or less at the same epoch, and the differences could rather be due to different interpretations of the same spectrum.

4.1. Radial velocities and equivalent widths

We investigated our 4 years of low-dispersion spectra in order to search for large, monthly to yearly variations. The radial velocity (RV) of the main spectral lines was measured by fitting a gaussian to the top (resp. bottom) of the emission (resp. absorption) lines. The EW was determined by integrating the profile in a window of about 8Å centered on the rest wavelength (such a large window was necessary because of the low resolution of the SMARTS data). The mean of the RVs and EWs and dispersion around this mean are presented in Table 1. Note that the RVs of He Iλ4471 appear systematically bluer than those of He IIλ4542 because of the contamination of the red wing of the He I line.

The RV and EW of the diffuse interstellar bands (DIBs) near Hα and C IV λ5812 were also measured. To get rid of possible remaining calibration problems, the observed RVs of these strong and rather narrow features were used to correct the RVs of the main lines, assuming the rest wavelengths from Herbig (1995) and that the average DIB RVs of the FEROS data were the actual ones (-13.6km s^{-1} for the DIB at 5780Å, -3.4km s^{-1} for the DIB at 6614Å). However, only a slight improvement is seen in the dispersion of the RVs after this correction.

The dispersion of the RVs appears rather constant among the measured lines (about 10km s^{-1}).

[3] The database of the All-Sky Automated Survey (ASAS) also contains some data on HD 148937, but they are not usable: as is often the case for relatively bright stars, even the photometry flagged as good appears somewhat erratic, probably because of saturation problems.

The mean RVs from the high-resolution data (FEROS, UVES, UCLES) are compatible with the SMARTS values within the error bars (see Table 1 - note there is no dispersion for UVES and UCLES data since there is only one exposure). It is however worth noting that He Iλ4471 and Hα, two lines affected by wind emission, present a higher dispersion of the RVs in the high-quality FEROS datasets. Our measurements are also in agreement with the RVs found in the literature (Conti et al. 1977; Augensen 1985). In addition, Conti et al. (1977) mentioned the compatibility of their results with those of Abt & Biggs (1972) and their average value of the velocity is also similar, within the errors, to those of Westerlund (1961); Buscombe & Morris (1960).

From spectroscopic data, we have thus established a dispersion of 10 km s^{-1} (=$\sigma_{\rm RV}$) on the radial velocities of HD 148937. Furthermore, no clear signature of binarity, like e.g. the presence of double-line profile, was detected in our data. Therefore, we conclude that no indication of binarity could be found on both the long-term (a few years) and short-term (a few days) ranges probed by the observations. This result agrees with the conclusion reached by Conti et al. (1977) and Garmany et al. (1980) on the constancy of the RVs[4].

However, it should be noted that the implications of the lack of significant RV variations in terms of the multiplicity of the star depend strongly on what assumptions we make about the orbital parameters of a putative binary. Indeed, unfavourable values of the orbital inclination, the mass ratio and the orbital period or a combination of several of these parameters could lead to rather small radial velocity variations. In this context, it is worth noting that RV variations similar to those found for HD 191612 (Nazé et al. 2007; Howarth et al. 2007) would be below our detection threshold. The simple approach of Garmany et al. (1980) enable us to evaluate the probability that we have missed a spectroscopic binary as a result of a low orbital inclination and for a given period and mass ratio. Taking the rather conservative assumption that the semi-amplitude of the radial velocity curve should be smaller than $2 \times \sigma_{\rm RV}$, and assuming a circular orbit and a mass of 55 M$_\odot$ for the Of?p star, we find that there is a less than 1.7% probability that HD 148937 is a binary with a period of 100 days or less and a mass ratio of 1. If we allow a mass ratio of 5 (i.e. a companion of spectral type ∼B2, the probability increases to 6 and 24% for periods shorter than 15 and 100 days respectively. Of course, the probabilities of missing a binary increase drastically if the orbit is no longer assumed to be circular and this would be especially relevant for a long-period binary system.

Looking at the EWs, three lines, He II λ 4686, Hβ, and Hα, present clearly deviant dispersions, suggesting intrinsic variability. Fig. 4 compares the RVs and EWs of Hα and the neighbouring DIB, presented with similar scales: the larger dispersion of the Hα EWs is obvious. We might note that these lines are the most sensitive ones to the wind.

4.2. Line profiles

To investigate further the variability found previously, we performed another test using the Temporal Variance Spectrum (TVS, Fullerton et al. 1996). No large, significant variation was found, except for the aforementioned variable lines and He I λ 6678. Values close to the significance threshold are however also found for N III $\lambda\lambda$ 4634,4641 (see Fig. 5).

Fig. 6 displays the line profile variations of Hα in the SMARTS data. Note that the changes occur on relatively short timescales, as underlined by our high-resolution data. In fact, two FEROS spectra taken on two consecutive nights do show the small scale variations in the He II λ 4686 and Hydrogen Balmer lines (see right side of the same figure for Hβ). Similar changes of the same lines are also found when comparing with the other high-resolution data. The variability is confirmed by looking at published tracings of the spectrum of HD 148937: in a spectrum taken in 1991 and reported in Nota et al. (1996), the Hβ and Hγ lines seemed to consist of two absorption components of equal strength in 1991, whereas the blue one is much stronger in our 2002-2003 high-resolution

[4]Using the same data as these authors, Hutchings (1976) had suggested the star to be a binary of period 9d, but this was never confirmed later. However, a problem was identified with some of the photographic plates (Conti et al. 1977).

spectra[5].

A period search was made on the RV and EW measurements using the techniques of Heck et al. (1985, see remarks of Gosset et al. 2001) and Lafler & Kinman (1965). No significant period was detected, except maybe for Hα, where a peak at about 7d seems to slightly stand out above the noise. We also performed a 2D Fourier test on the SMARTS spectra themselves, in regions centered on the Hα, Hβ, and He II λ 4686 lines. The periodogram was then averaged on the wavelength interval (see the result in Fig. 7). This time, without ambiguity, a period of 7.031$\pm$0.003 is clearly detected for Hα. When folded with this period, the RVs and EWs of Hα actually follow a regular pattern (Fig. 8). This frequency is also present in the periodograms of Hβ and He II λ 4686, though with a reduced intensity. A short-term monitoring, preferentially done with a high resolution spectrograph, should better constrain the properties of this periodic phenomenon.

On the contrary, other lines, among which He I and C III λ 4650, appear remarkably constant for an Of?p star. In that regard, the 1995 UCLES data could be a carbon copy of the latest FEROS data. Even older observations, taken by J.-M. Vreux in June 1974 and B. Westerlund in July and August 1974, show similar features, without any striking differences. The only reference to a possible change of these lines can be found in Westerlund (1961): 'Practically all spectra have He II λ 4686 in emission, most of them also N III λ 4641 and a few also C III (?) λ 4651' - without having access to the actual plates, it is difficult to judge what happened that year, but maybe the crude photographic plates might be to blame. Without further information, it is difficult to judge the significance of this report; all we can say is that such a behavior is not seen in intensive, higher quality, subsequent data.

4.3. Physical parameters

The visible spectrum can also be used to derive the physical parameters of HD 148937. For example, the line width reflects the projected rotation velocity of the star. Avoiding the variable Balmer Hydrogen and He II lines and the contaminated He I lines, we applied the Fourier method (see Simón-Díaz & Herrero 2007, and references therein) on the metal lines of C IV λ 5812 and O III λ 5592. This results in $v\sin(i)$ of 58km s^{-1} for the former and 45km s^{-1} for the latter, and we therefore conclude that $v\sin(i) \gtrsim$ 45km s^{-1}. This value is much lower than those found in the literature (200km s^{-1}, Conti & Ebbets 1977; 92km s^{-1}, Penny 1996; 76km s^{-1}, Howarth et al. 1997), but this is not surprising since the other methods do not permit one to disentangle the rotational broadening from other broadening mechanisms (i.e. macroturbulence, Simón-Díaz & Herrero 2007).

An average of our FEROS spectra was fitted using CMFGEN (Hillier & Miller 1998, for a description of the models and of the method, see also Martins et al. 2005b; Bouret et al. 2005), as shown in Fig. 9. Note that, if the central part of the Balmer lines is contaminated by emission, the wings remain sufficiently clean to be used for gravity estimates. The best fit gives $T_{eff} = 41000 \pm 2000$K, $\log(g) = 4.0 \pm 0.1$, $R/R_\odot = 15.0 \pm 2.5$ and $\log(L/L_\odot) = 5.75 \pm 0.1$ (assuming He/H of 0.08 and a distance of 1.38 kpc, see below). Such values are comparable to those of O5-6 V/III stars (Martins et al. 2005).

The abundance of nitrogen appears to be N/H=3 $\times$ 10^{-4} (with an uncertainty of 40%), which for a solar reference value of 7$\times$10^{-5} (Asplund 2005) corresponds to an overabundance of a factor 4 compared to the Sun. This overabundance indicates that the star is already chemically evolved, showing products of the CNO cycle at its surface. This result is compatible with abundance estimates in the surrounding nebula, thought to consist at least partly of material ejected by the star (0.7 dex enrichment in N, see Dufour et al. 1988).

In addition, we estimated the mass-loss rate from the P Cygni profiles of an archival IUE spectrum. A rather high clumping factor (f=0.01) was required to prevent N IV λ 1720 (and to a lesser extent O V λ 1371) from being too strong. This value was also found by Bouret et al. (2005) in their study of two O4 stars. With this clumping factor, N IV λ 1720 and Si IV $\lambda\lambda$ 1393,1403 are reasonably reproduced for a mass loss rate lower than 1–

[5] We might also note that from objective prism data, Mac Connell & Bidelman (1976) reported that the Hβ line of HD 148937 was 'filled in' but without a tracing, we can't compare their result with ours in detail.

$2{\times}10^{-7}M_{\odot}yr^{-1}$. However, N V $\lambda\lambda$ 1238,1242 and C IV $\lambda\lambda$ 1548,1550 remain too strong as long as $\dot{M}$ is larger than $\sim 10^{-8}M_{\odot}yr^{-1}$. Given the evidence for non spherical emission in the star (see below), we refrained from going into too much detail in this analysis. One can simply conclude that a mass-loss rate of $10^{-7}M_{\odot}yr^{-1}$ (corresponding to $\dot{M}_{uncl} = 10^{-6}M_{\odot}yr^{-1}$) is a conservative upper limit on the mass loss rate of HD 148937. Note that the prefered value for the terminal velocity amounts to 2600km s^{-1}.

The fit appears rather good (see Fig. 9), except for two caveats. First, we note that all the observed He I and He II lines appears to be stronger than in a model with He/H=0.1, but reducing this ratio to 0.06 does not completely solve the problem. A similar difficulty was uncovered when fitting the spectrum of HD 191612 (Walborn et al. 2003) and the origin of this discrepancy remains unclear at the moment (dilution by an hidden companion? contamination by emission?). Increasing the slope of the velocity field (the classical β parameter) does not help to weaken systematically all He lines. Second, it is impossible to reproduce the visible emission lines with the mass-loss rate and terminal velocity estimated from the UV P-Cygni profiles. The Balmer and He II emissions are narrow and cannot be explained (only) by a spherical wind emission as derived in the UV. Therefore, the wind should consist of two components: a spherical one (the only one CMFGEN is able to reproduce) and a non-spherical one where the narrow Balmer emissions arise (e.g. a disk).

4.4. Summary

Contrary to HD 108 and HD 191612, HD 148937 does not display spectacular line changes for H, He I and C III λ 4650. However, it does show small-scale variations of the He II λ 4686 and Hydrogen Balmer lines. Looking closely at the Hα line, a period of 7.031d is detected on our low-resolution observations, but requires confirmation as the temporal sampling was not optimized for such short timescales.

The two other Galactic Of?p stars actually also display some small-scale changes, in addition to the main, large variations. For HD 108, it can be easily spotted when comparing observations taken during one observing run (see e.g. Fig. 10, reproduced from Nazé 2004). For HD 191612, Howarth et al. (2007) found 'small-amplitude variability ... on timescales longer than a few days'. It is not yet known if these changes are stochastic or periodic, as the observations were not optimized to detect such short-term variations.

Although of small amplitude, the phenomenon observed for HD 148937 could still be related to those observed in the other Of?p stars. On the one hand, the variations of HD 148937 could represent a scaled-down version of those observed for HD 108 and HD 191612, since these changes are similar in character. As the H and He II λ 4686 variations were clearly the largest for these objects, it is possible that the He I and C III changes would then remain undetected for HD 148937. The lower amplitude of the variability for HD 148937 might be linked to a relaxation of the system following the eruption that gave rise to the bipolar nebula NGC6164-5, or could be related to a lower angle between the rotation and magnetic axis (in the case of the magnetic oblique rotator model, as proposed for HD 191612[6]). On the other hand, it is equally possible that these small-scale changes are similar to the short-term variations seen in HD 108 and HD 191612. It would then remain to explain their periodicity in HD 148937, and see if the small-scale changes are periodic for the other two objects. In this case, larger variations could be present in HD 148937, but only with a much longer timescale than for HD 108 since we see no significant changes of He I and C III between 1974, 1995 and 2002-5 data.

5. X-ray data

The X-ray emission of HD 148937 was first discovered with the *Einstein* satellite. The star appears as source 2E1630.1−4800 in the *Einstein* 2E catalog (Harris et al. 1994). It has an IPC count rate of 0.100±0.004 cts s^{-1} (Harris et al. 1994) or 0.114±0.004 cts s^{-1} (Chlebowski et al. 1989). More recently, it was observed by the ROSAT satellite, notably during the All-Sky Survey, where it appears as source 1RXS J163352.2−480643 (also known as 1RXP J163352.9−480635), with a PSPC

[6]In this case, the 7d period would reflect the rotation period of the star. The magnetic field should therefore be weaker than for HD 191612 since, although the star is old enough to have undergone eruptions, the field has not slowed the rotation to very long timescales as found for HD 191612.

count rate of 0.23±0.03 cts s^{-1}. ROSAT has also observed HD 148937 during three pointed observations (collected under the id # RP900379). The first observation was made in September 1992 during 3.35 ks, the second was taken in March 1993 during 10.14 ks and the last one in August 1993 for 5.36 ks. After downloading these data from the archives, we estimated PSPC count rates for these observations to 0.197±0.008 cts s^{-1}, 0.189±0.004 cts s^{-1}, and 0.203±0.006 cts s^{-1}, respectively.

More recently, the star was observed by XMM-*Newton*, whose high sensitivity permits a deeper analysis of its high-energy emission. The EPIC-MOS spectra of HD 148937 were extracted over a circular region with radius 50″centred on the star; the background was extracted in the surrounding annular area of outer radius 75″. For EPIC-pn, the radius of the source region was limited to 37.″5 in order to avoid a nearby gap; we then use as background a nearby circle devoid of sources. The EPIC spectra, binned to get a minimum of 10 cts per bin (i.e. S/N≥3 in each bin), are shown in Fig. 11 where pn data is presented in green, MOS1 in black and MOS2 in red.

The spectrum appears thermal, and the Fe XXV line at 6.7keV is present. We have adopted a distance of 1.38 kpc (based on the membership in the Ara OB1a association, see Humphreys 1978) and an interstellar column density N_H of $4{\times}10^{21}$ cm^{-2} (Diplas & Savage 1994). In the spectral modelling, we do not allow the absorption to go below this threshold. In addition, since both datasets gave consistent results, within the errors, we finally fit all data simultaneously. The results are very similar to those of HD 108 and HD 191612: fits using only one thermal component were unacceptable ($\chi^2 > 2$) whereas the sum of two absorbed[7], optically thin equilibrium plasma models (*mekal*, Kaastra 1992) is much better. In the latter case, two solutions with similar residuals are found: one with temperatures kT around 0.6 and 2 keV and negligible absorbing columns; the other with lower temperatures (0.2 and 1 keV) and larger columns ($N^{\rm H} \sim 0.5$ and 1×10^{22} cm^{-2}). The second is slightly better and also favored by the results of a fit by a differential emission-measure model (DEM, *c6pmekl*, Lemen et al. 1989; Singh et al. 1996). The low-temperature peak is generally explained by instrinsic wind-wind shocks, whereas the high-temperature feature could be related to colliding winds in a binary or to shocks in a magnetically confined wind (Zhekov & Palla 2007). If we assume the latter origin, it is important to note that the importance of this second peak is much lower than for well-known magnetic system such as θ Ori^{1}C or τSco (Zhekov & Palla 2007).

As HD 148937 is brighter and closer than the two other galactic Of?p stars, the noise on its X-ray spectrum is reduced. This helps to spot a small deficiency of the aforementioned model at low energies. The fit can be improved by the addition of a third *mekal* component. Two solutions are again found, each corresponding to the two solutions mentioned above plus a third cooler component. Although the 'hot' solution (kT of 0.2, 0.6 and 2keV) presents a better χ^2 than the 'cool' one (kT of 0.1, 0.2 and 1keV), it appears worse at low energies.

The results of these fits are reported in Table 2, where the unabsorbed fluxes $f_{\rm X}^{\rm unabs}$ (in the 0.4–10.keV range) are corrected only for the interstellar absorbing column. For each parameter, the lower and upper limits of the 90% confidence interval (derived from the ERROR command under XSPEC) are noted as indices and exponents, respectively. The normalisation factors are defined as $\frac{10^{-14}}{4\pi D^2}\int n_e n_{\rm H} dV$, where D, n_e and $n_{\rm H}$ are respectively the distance to the source, the electron and proton density of the emitting plasma.

Using typical colors and bolometric corrections from Martins & Plez (2006) and the optical properties of HD 148937 (V=6.728, $B-V$=0.343, Maíz-Apellániz et al. 2004), the bolometric luminosities amounts to $L_{\rm BOL} \sim 2 \times 10^{39}$ erg s^{-1}, a value in agreement with the results of model atmosphere fits. The X-ray luminosities $L_{\rm X}^{\rm unabs}$, evaluated from the EPIC data in the 0.5–10.0 keV range and corrected for interstellar absorption, is $\sim 2 \times 10^{33}$ erg s^{-1}, resulting in $\log(L_{\rm X}^{\rm unabs}/L_{\rm BOL}) \sim -6$. Again, as for HD 108 and HD 191612, the value of this ratio is much larger (about 8 times here) than that of the 'canonical' relation (Sana et al. 2006). In this context, it is interesting to note that for the 2T fit, only 30% of the unabsorbed flux comes from the high-temperature component

[7]Since these two thermal components could arise in different regions of the wind, we allow them to be absorbed by independent column densities ($N^{\rm H}$).

(in comparison, it is 25% for HD 108 and 27–35% for HD 191612): this means that the presence of a high-temperature component is not the only reason for the overluminosity.

Finally, we also analyze the X-ray lightcurves. First, one ought to note that the ROSAT data and *Einstein* count rates of HD 148937 agree well with the spectral properties derived from the XMM-*Newton* observations (Fig. 12). Second, lightcurves were derived from the XMM-*Newton* datasets for a large range of energy domains and time bins. They were subsequently analyzed by χ^2 and *pov* tests (Sana et al. 2004) but no significant variation was found. It therefore appears that the flux of HD 148937 at X-ray energies is constant, within the error bars, on short-term ranges (over the duration of an observation) as well as on timescales of decades.

5.1. High resolution (RGS)

The high-resolution (RGS) X-ray spectrum of HD 148937 is presented in Fig. 13. Although the signal-to-noise ratio is limited and in no ways comparable to that obtained for RGS spectra of closer objects, it is nevertheless possible to get some information from it. First, a global fit was undertaken: the lines were fitted by triangular profiles, which are particularly suited to get an idea of their width and their decentering (if any), while the residual continuum was fitted by a bremsstrahlung model. Only the amplitude of the triangles was allowed to vary from line to line, the overall shape being uniform. The best fit results in a line center position of -195 ± 707km s^{-1}, a red edge at 1163 ± 512km s^{-1}, and a blue edge at -2327 ± 657km s^{-1}, resulting in a FWHM of 1745 ± 416km s^{-1}. The X-rays lines are thus quite large and do not present significant blue/redshift, but their profiles are slightly skewed. In this context, it might also be interesting to note that the Ne IX/Ne X ratio for this O6 star fits nicely in the sequence found by Walborn (2007).

To get more precise information, we decided to focus on the O VIII λ 18.97 Lyα line, the strongest feature in the spectrum that is rather free from blends with other lines. The line is broadened and has a FWHM around 2500 km s^{-1}. A binned version of the data suggests that the line might display some structure (which could actually also be present on the Lyβ line, see below). We have attempted to fit the O VIII Lyα line with a exospheric line profile model following the formalism of Kramer et al. (2003). The main assumptions are that the X-ray emission originates from material distributed throughout a spherical wind, above a radius $r \geq R_0 > R_*$ and that the hot plasma follows the bulk motion of the cool wind. Doppler broadening due to macroscopic motion hence provides the main source of line broadening. The line emissivity is assumed to scale as $\epsilon \propto \rho^2 r^{-q}$ where the r^{-q} term accounts for a radial dependence of the filling factor of the X-ray plasma. The free parameters of this model are thus R_0, q (that we take equal to zero here) and $\tau_{\lambda,*} = \frac{\kappa_\lambda \dot{M}}{4\pi v_\infty R_*}$, the characteristic optical depth at wavelength λ. For the terminal wind velocity, we have first adopted $v_\infty = 2285$ km s^{-1} as derived by Howarth et al. (1997). The best fit to the unbinned line profile is obtained for $R_0 \simeq 2.25\,R_*$ and $\tau_{\lambda,*} = 0$. However, larger values of $\tau_{\lambda,*}$ are also possible for larger R_0. The fits to the binned profiles roughly confirm this picture, but bring up another (actually deeper) minimum in the χ^2 contours around $R_0 \simeq 1.65\,R_*$ and $\tau_{\lambda,*} = 0.4$. While the unbinned data hence favour a flat-topped profile, the binned spectra rather suggest a skewed profile. In any case, we note that the fits suggest a rather broad line.

We have applied the same procedure to the O VIII λ 16.01 Lyβ line. The best fit is obtained for $R_0 \simeq 1.85\,R_*$ and $\tau_{\lambda,*} = 0$, in reasonable agreement with the results obtained for the Lyα line. Note that the strong Ne X λ 12.13 Lyα line is probably blended with another line on its red side[8] and can thus not be fitted easily with our model.

We have repeated the fits of the O VIII λ 18.97 Lyα and λ 16.01 Lyβ lines with the same exospheric model and the same parameters as before, except for the terminal velocity where we adopted $v_\infty = 2600$ km s^{-1} instead (see section 4.3 above). The shape of the χ^2 contours is essentially the same as found before with $v_\infty = 2285$ km s^{-1}, but, as can be expected from the increase of the wind velocity, the minimum is shifted to somewhat lower values of R_0. In fact, the best fit

[8]There are a number of lines from various iron ions (e.g. Fe XXIII λ 12.193, Fe XVII λ 12.264 and Fe XXI λ 12.286) that could possibly be responsible for this blend. Given the presence of other strong lines of this ion, Fe XVII is probably the best candidate.

to the unbinned Lyα line profile is now obtained for $R_0 \simeq 2.05\,R_*$ and $\tau_{\lambda,*} = 0$. The fits to the binned profiles now yield the lowest χ^2 around $R_0 \simeq 1.45\,R_*$ and $\tau_{\lambda,*} = 0.0$. For the Lyβ line, the best fit remains at $R_0 \simeq 1.85\,R_*$ and $\tau_{\lambda,*} = 0$.

Over recent years, the He-like triplets, consisting of a forbidden (f), an intercombination (i) and a resonance (r) lines, of various ions have been used as plasma diagnostics for a number of O-type stars (see e.g. Leutenegger et al. 2006; Oskinova et al. 2006). In fact the $\mathcal{R} = f/i$ ratio has been shown to be a sensitive diagnostic of the dilution of the UV radiation field in the line emission region (e.g. Porquet et al. 2001). In the case of HD 148937, the only He-like triplet with a reasonable level of exposure is the Ne IX triplet at $\lambda\lambda$ 13.447 (r), 13.548 + 13.551 (i) and 13.697 (f). However, even for this complex the data do not allow us to perform a quantitative fit of the line strengths. Still, the data show that the $\mathcal{R} \sim 1$ (see Fig. 14). Hence this ratio must be below its collision equilibrium low-density limit of $\mathcal{R}_0 = 3.1$ (Leutenegger et al. 2006). Note also that the f component could be blended with unresolved Fe XIX lines at $\lambda\lambda\,13.73 - 13.74$. These features could lead to an overestimate of the actual strength of the f line. The reduced strength of the f component of the Ne IX triplet is quite typical for O-stars (see e.g. Oskinova et al. 2006).

6. Conclusions

With its strong C III $\lambda\,4650$ lines, HD 148937 is a true Of?p star. However, it is unclear if it constitutes a perfect 'twin' of HD 108 or HD 191612. This paper reports a first thorough, multiwavelength variability study of HD 148937.

In the visible domain, its photometry does not change much, and its S-Dor status can not be confirmed. The visible spectrum does vary, but the changes are limited to the main lines formed in the stellar wind, i.e. the Balmer Hydrogen lines and He II $\lambda\,4686$. This variability occurs with very small amplitudes and an analysis of the changes in the Hα line reveals a periodicity of 7.031$\pm$0.003d. However, the He I and C III lines seem constant. In addition, no large ($>$10km s^{-1}) variations of the RVs could be identified and no other typical signature of binarity (e.g. blended spectrum) was detected. Finally, model atmosphere fits yield parameters typical of an O5-6V/III star; they also suggest the presence of a non-spherical component to the stellar wind.

In the X-rays, the spectrum appears thermal in nature, with a dominant cool component (0.2keV), broad unshifted X-ray lines, and an order-of-magnitude overluminosity compared to normal O-type stars. It looks nearly identical to those of HD 108 and HD 191612, though with a larger flux (because of the smaller distance) and thus a better signal-to-noise ratio. No significant short-term or long-term variation of the X-ray flux could be brought to light.

Three stars in our Galaxy share a very peculiar spectral characteristic, the presence of strong C III lines. Is HD 148937 completely similar to the other two? Using only the X-ray results, the answer would be clearly yes. From the visible spectroscopy, however, the answer is unclear. The variability of HD 148937 could either be related to the small-scale changes or to the large variations seen in HD 108 and HD 191912. Considering the former, additional data are needed to find if these small-scale changes are truly periodic for the other Galactic objects, and therefore determine the origin of this short-term, small-scale variability. In this case, it also remains to be seen if HD 148937 presents large variations of its H, He I, and C III lines - from our dataset, this can only occur on very long timescales (likely even larger than the 55yrs of HD 108). On the other hand, the small-scale changes of HD 148937 could represent a scaled version of the phenomenon observed in HD 108 and HD 191912, thereby explaining the lack of variations of the He I and C III lines. In this case, the 538d period of HD 191612 and the 55yrs timescale of HD 108 would here be replaced by a much shorter, $\sim$7d period.

To ascertain the origin of this variability and constrain more its properties, additional data are clearly needed: short-term monitoring of HD 108 and HD 191612, long-term observations at high resolution and spectropolarimetry of HD 148937.

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Fig. 1.— Hipparcos photometry of HD 148937.

Fig. 2.— Visible spectrum of HD 148937 (median combination of our four FEROS spectra). The most important lines are labeled and tickmarks are drawn at their rest wavelengths.

Fig. 3.— RVs and EWs of the He I λ4471 and He II λ4542 lines, and the ratio of the EWs. SMARTS data are presented by filled circles and for the right panel, FEROS by stars, UVES by a cross (shown at HJD+1000.), UCLES by an open triangle (shown at HJD+4000.). The limits for the spectral types come from Conti & Alschuler (1971); Conti & Frost (1977).

Fig. 4.— RVs and EWs of Hα and the DIB at λ6613.62Å, shown on the same scale (SMARTS data only).

Fig. 5.— TVS and mean low-resolution spectrum of HD 148937.

Fig. 6.— Left: long-term variability of the Hα line in the 2006 low-resolution spectra (from month to month). Similar figures can be drawn for the other years of the campaign. Right: variability of the Hβ line in our FEROS spectra (2003: dotted line and black solid line for observations taken on May 24 and 25, respectively; 2004: thin dashed line, 2005: thin solid line).

Fig. 7.— Top: Periodogram derived from the SMARTS spectra covering the Hα line (see text). Bottom: Spectral window of the observations.

Fig. 8.— RVs and EWs of Hα phased with a period of 7.031d (T_0 was arbitrarily chosen as HJD=2 452 680).

Fig. 9.— Comparison of the average FEROS spectrum of some lines (solid black line) and their best fit CMFGEN model (dash-dot red line, for $\log(\dot{M}) = -7.5$ and the parameters listed in Sect. 4.3). This figure only appears in colors in the electronic version of the journal.

Fig. 10.— The Hβ line profile in the spectrum of HD 108 appeared particularly variable during our observing run of 2001: the thin solid line shows the spectrum taken on Sept. 10, the thick solid line the spectrum taken on Sept 11, dotted lines the spectra taken on Sept. 13 and 15, and dashed lines the spectra taken on Sept. 18.

Fig. 11.— EPIC X-ray spectrum of HD 148937 with the best-fit $3T$ model. The EPIC-pn data (drawn in green) appear at higher ordinates that those of the two EPIC-MOS (shown in black and red for MOS1 and 2, respectively). This figure only appears in colors in the electronic version of the journal.

Fig. 12.— Normalized count rate: the ROSAT and *Einstein* count rates were divided by the count rate expected from the best-fit $2T$ model. A value of 1 indicates that no flux change has occurred.

Fig. 13.— Binned (3 channels per bin), combined (RGS1+2, 1st and 2nd order) X-ray spectrum of HD 148937. The most important emission lines are labeled. Note that the spectrum was not smoothed.

Fig. 14.— The Ne IX fir He-like triplet in the RGS spectrum of HD 148937. The rest wavelengths of the different components are indicated by the labels. The f component is clearly suppressed compared to the collision equilibrium low-density value of $\mathcal{R}_0 = 3.1$.

Table 1: Mean and dispersion of the measured RVs and EWs.

Line	EW interval (Å)	RV_{smarts} ($km\,s^{-1}$)	EW_{smarts} (Å)	RV_{feros} ($km\,s^{-1}$)	RV_{ucles} ($km\,s^{-1}$)	RV_{uves} ($km\,s^{-1}$)
He II λ 4199.83	4193.83–4205.83	−46.0±12.2	0.495±0.054	−38.0±1.4	−40.3	−41.3
He I λ 4471.512	4465.512–4475.	−59.3±10.4	0.325±0.034	−41.0±8.1	−30.7	−51.3
He II λ 4541.59	4535.–4548.18	−38.7±7.5	0.683±0.035	−32.2±2.0	−32.0	−33.1
N III λ 4634.25	4631.–4644.25	−24.4±7.3	−0.963±0.067	−29.7±4.6	−31.3	−26.7
N III λ 4641.02		−37.4±6.7		−43.6±0.3	−50.2	−44.3
C III λ 4650	4644.25–4653.40		−0.470±0.037			
He II λ 4685.682	4679.682–4691.682	−8.8±7.5	−0.761±0.079	−18.3±4.7	−22.8	−19.4
Hβ λ 4861.33	4645.33–4877.33	−191.2±11.9	1.218±0.120	−182.0±4.6	−185.0	−187.7
C III λ 5695.92	5689.92–5701.92	−34.7±11.9	−0.205±0.041	−22.1±0.4	−28.9	−23.2
DIB λ 5780.45	5774.45-5786.45	−19.8±11.0	0.515±0.045	−13.6±0.5	−15.1	gap
C IV λ 5811.98	5805.98–5817.98	−49.3±13.6	0.196±0.035	−33.3±3.6	−29.6	gap
C IV λ 5812 (cor.)		−42.7±8.6				
Hα λ 6562.85	6550.85–6574.85	3.0±12.6	−1.176±0.237	−7.1±7.6	−2.3	−12.4
Hα(cor.)		2.2±12.9				
DIB λ 6613.42	6609.42–6617.42	−2.2±10.4	0.106±0.020	−3.4±1.1	−8.5	−5.2

Table 2: Best-fitting models and X-ray fluxes at Earth.

Type	$N_1^{\rm H}$	kT_1	$norm_1$	$N_2^{\rm H}$	kT_2	$norm_2$	$N_3^{\rm H}$	kT_3	$norm_3$	χ^2_ν(dof)	$f_{\rm X}^{\rm abs}$	$f_{\rm X}^{\rm unabs}$
	10^{22} cm^{-2}	keV	10^{-3}cm^{-5}	10^{22} cm^{-2}	keV	10^{-3}cm^{-5}	10^{22} cm^{-2}	keV	10^{-3}cm^{-5}		(in 10^{-12} erg cm^{-2} s^{-1})	
2T	$0.49_{0.46}^{0.51}$	$0.23_{0.22}^{0.23}$	$33.9_{28.7}^{39.4}$	$1.03_{0.957}^{1.12}$	$1.34_{1.31}^{1.37}$	$4.42_{4.24}^{4.61}$				1.34 (1804)	3.0	7.0
3T cool	$0._{0.}^{0.06}$	$0.08_{0.08}^{0.09}$	$19.5_{16.7}^{36.5}$	$0.55_{0.51}^{0.57}$	$0.23_{0.23}^{0.24}$	$38.4_{30.4}^{43.3}$	$1.23_{1.13}^{1.33}$	$1.37_{1.33}^{1.40}$	$4.52_{4.32}^{4.73}$	1.23 (1801)	3.1	8.6
3T hot	$0._{0.}^{0.01}$	$0.25_{0.24}^{0.26}$	$1.57_{1.49}^{1.71}$	$0.35_{0.31}^{0.39}$	$0.63_{0.62}^{0.64}$	$3.43_{3.10}^{3.74}$	$0.53_{0.44}^{0.63}$	$2.00_{1.90}^{2.11}$	$2.25_{2.11}^{2.39}$	1.13 (1801)	3.2	7.8