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Optical Spectroscopy of Colliding-Wind Systems to be Observed with XMM[1]

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Abstract. We present the very first results of an optical spectroscopy campaign targeting colliding-wind candidates of the young open cluster NGC 6231 that are going to be observed with the XMM satellite as part of the Liège Project for Guaranteed Time Observations. We derive new improved orbital solutions and discuss the spectral characteristics of these systems. Special attention is paid to the binary star HD 152248. We investigate its He II λ4686 and Hα lines and their profile variability. We discuss the probable signature of a wind-interaction process in order to derive constraints on the properties of the shock region.

1. Introduction

Massive O stars have strong stellar winds associating large mass-loss rates and high terminal velocities. Within a binary system, we expect that the winds from both stars interact, leading to the formation of a shock region (Stevens, Blondin, & Pollock 1992). This interaction can manifest itself through enhanced X-ray emission which can show phase-locked variability due to the variation of the column density of absorbing matter along the line of sight. The recent launch of ESA's X-ray Multi Mirror (XMM) satellite offers now the prospect of substantial breakthroughs in the field of colliding winds. But the search for wind collision signatures is not limited to the X-ray domain. The enhanced density in the shock region can also contribute to the formation of optical emission lines through the recombination process. When analyzing XMM observations, optical spectral information and accurate ephemerides will be of major importance. We focus here on the massive binary systems of the young open cluster NGC 6231 that are going to be observed with XMM.

Situated at a distance of 1.99 kpc (Baume, Vasquez, & Feinstein 1999), the cluster NGC 6231 is considered as the nucleus of the rich Sco OB 1 association.

[1]Based on observations collected at the European Southern Observatory (La Silla, Chile) and at the Cerro Tololo Inter-American Observatory (CTIO).

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It harbors an interesting sample of single O-stars as well as massive O-star binaries and a Wolf-Rayet binary (WR 79). NGC 6231 will be observed with the XMM satellite for a total duration of 180 ksec. The pointing will be centered on the massive binary HD 152248. Four other known massive binaries lay within the XMM field: HD 152218, HD 152219, CPD −41°7733 and CPD −41°7742.

This paper is organized as follows. After a brief description of the observations, we provide new orbital solutions and new spectral types for some of the studied systems. Next, we discuss the previous X-ray observations of the cluster by the ROSAT satellite. Finally we consider the HD 152248 system more in detail and we focus on its He II λ4686 and Hα lines and their profile variability.

2. Observations

An extensive observing campaign spread over the last few years has allowed us to obtain spectra for most of the O stars surrounding HD 152248. The data were collected using several instruments at the European Southern Observatory (ESO) and at the Cerro Tololo Inter-American Observatory (CTIO). Table 1 summarizes the main features of the instrumental configurations and of the observations. We refer to a forthcoming paper for a more detailed description.

Table 1. Instrumental configurations and observations

Telescope	Instrument	Spectral Range	Resolution	Observed Systems
ESO 1.5m	Boller&Chivens	3790-4765Å	4000	a
ESO CAT[1]	CES[2]+LC[3]	4450-4490Å	60000	a
	CES+LC	4665-4705Å		a
	CES+VLC[4]	4460-4480Å	75000	a, b, c, d, e
	CES+VLC	4675-4795Å		a
ESO 1.5m	FEROS	3650-9200Å	48000	a, b, c, d, e
CTIO 1.5m	BME[5]	3850-5790Å	45000	a, b

1. Coudé Auxiliary Telescope	a. HD 152248
2. Coudé Echelle Spectrograph	b. HD 152218
3. Long Camera	c. HD 152219
4. Very Long Camera	d. CPD −41°7733
5. Bench-Mounted Echelle spectrograph	e. CPD −41°7742

3. Orbital Solutions and Spectral Types

We measured the Doppler shifts and radial velocities (RVs) from the He I λ4471 line and we derived improved periods using both the Lafler and Kinman method (Lafler & Kinman 1965) and a Fourier analysis. We then adopted the value that yields the lowest *rms* scatter of the RVs around the orbital solution. The latter were obtained using an improved version of the Wolfe, Horak and Storer algorithm (see Wolfe, Horak, & Storer 1967 for the method and Rauw et al. 2000 for the implemented modifications). Table 2 presents preliminary orbital solutions for some of the observed systems.

We emphasize that the CPD $-41°7742$ system was previously reported as an SB1 system. However, we were able to disentangle the spectra of the primary and secondary stars and, for the first time, we present here a preliminary orbital solution for both components of the system.

We also note that our orbital solution for HD 152248 yields a larger value of the longitude of periastron than the value (76.9°) previously derived by Stickland et al. (1996). This could be due to apsidal motion.

Table 2. New orbital solutions based on the He I $\lambda4471$ absorption line. The usual notations have been used for the orbital elements. T_0 is the time of the periastron passage.

SB2 Systems	HD 152248		HD 152218		CPD $-41°7742$	
Spectral Types	O7.5III+O7III		O8.5V+O9.5?		O9V+O9.5?	
P(days)[fixed]	5.8116083		5.55679		2.4408	
e	.130	± .007	.269	± .038	.092	± .038
$\omega(°)$	86.6	± 5.6	118.8	± 9.9	157.7	± 15.4
T_0(JD -2450000)	2003.912	± .085	1387.707	± .138	1348.397	± .097
γ_1 (km s^{-1})	−28.6	± 1.8	−21.0	± 6.2	−21.9	± 3.5
K_1 (km s^{-1})	219.4	± 1.5	165.8	± 5.4	171.6	± 3.9
γ_2 (km s^{-1})	−29.1	± 4.7	−49.2	± 17.2	−26.8	± 13.0
K_2 (km s^{-1})	215.4	± 5.5	214.0	± 19.5	300.2	± 15.3

With respect to the forthcoming X-ray data, other precious information that can be obtained from the optical spectra are the spectral types and the luminosity classes. We respectively used the criteria of Conti (1973) and Mathys (1988; 1989) and Table 2 lists the preliminary classifications we derived.

4. X-ray data

The NGC 6231 cluster has also been observed in the X-ray domain with the ROSAT satellite. One observation was obtained with the High Resolution Imager and three others were done with the Position Sensitive Proportional Counter (PSPC). Some results from these pointings were presented by Corcoran (1996; 1999). It clearly appears from these data that most of the O-stars of the cluster are detected at X-ray energies. We retrieved the PSPC data from the HEASARC archive and we reprocessed them using the XSELECT software. We fitted the PSPC spectra with an absorbed single-temperature Raymond-Smith model (Raymond & Smith 1977) keeping the H I column density at $N_{H,ISM} = 0.311 \times 10^{21}$ cm^{-2} (corresponding to an extinction of $A_V = 1.4$). Our analysis reveals that all the binaries in our sample display an enhanced L_X/L_{bol}

ratio compared to the $L_X \simeq 10^{-7} L_{bol}$ relation valid for single OB stars (e.g. Berghöfer et al. 1997) and are therefore good colliding-wind candidates.

5. HD 152248

The brightest X-ray source in NGC 6231 is the eclipsing, double-line spectroscopic binary HD 152248 (Mayer, Lorenz, & Drechsel 1992). The orbital inclination i is about 72° (Penny, Gies, & Bagnuolo 1999). The components of HD 152248 have previously been classified as supergiants. However, this luminosity class is not consistent with the presence of He II λ4686 and Hα in absorption in the spectra of both components and we thus prefer a giant classification as mentioned in section 3.

5.1. The He II λ4686 and Hα lines

The He II λ4686 and Hα lines consist of two absorption components superimposed on a broader emission. A first analysis reveals that the absorption components closely follow the orbital motion and can thus be attributed to the primary and secondary stars.

In an attempt to isolate the emission component, we first model the He II λ4686 line by fitting three gaussians (two for the absorption components and one for the emission) on a spectrum where both absorption lines are well separated. We then shifted the templates of the absorption lines according to our orbital solution and to the phase of the observation and we subtract them from the raw spectra. This crude 'restoration' method yields rather good results between $\phi \simeq 0.1$ and 0.4, but at other phases we notice some artefacts which probably result from slight intensity variations of the absorption components in a way similar to what we observe in the He I λ4471 line.

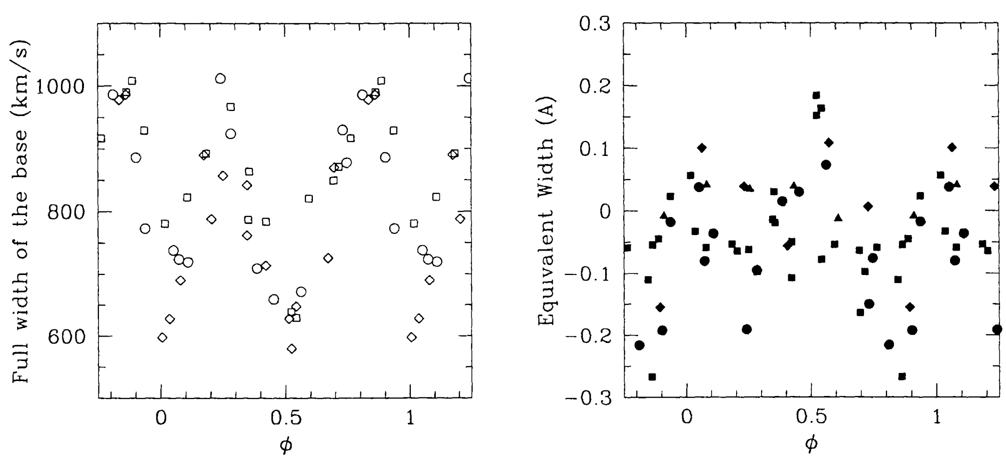

Figure 1. Left: Full width of the base of the emission component of the He II λ4686 line as measured on reconstructed spectra. Right: EWs of the He II λ4686 line as measured on raw spectra. Different symbols refer to different instruments: triangle=BME, square=B&C, diamond=CES, circle=FEROS.

Nevertheless we used the reconstructed spectra to measure the width of the base of the emission component. The results displayed in Fig. 1 show a strong phase-locked variation. The emission appears broader near phase 0.25 and 0.75 and narrower near conjunction phases. One could object that this is an artefact due to the reconstruction method, as the separation between primary and secondary lines is wider near $\phi = 0.25$ and 0.75 and narrower near 0.0 and 0.5. To check this, we have carried out the same measurements on the raw spectra and we recovered a similar pattern of variations.

We also measured the equivalent widths of the He II λ4686 line from 4676Å to 4696Å on the raw spectra (see Fig. 1). Though there is a larger scatter in the measurements, it is clear that absorption dominates near $\phi = 0.5$, and in a less clear-cut way near $\phi = 0.0$, and that emission dominates near $\phi = 0.8$.

The same techniques have been applied to the Hα line, which is much stronger than the He II λ4686 line. Though our Hα data are much less numerous, a clear similarity appears between the properties of the Hα and He II λ4686 lines.

5.2. A colliding-wind model

Since the components of HD 152248 are rather similar, we expect that the interaction takes place at equal distance from both stars and the contact surface between the winds should be roughly planar. This simple model can match the general properties of the emission components of the He II λ4686 and Hα lines, assuming they originate from the interaction region. Indeed, we expect the radial velocity distribution of the particles in the shocked region to be wider near $\phi = 0.25$ and $\phi = 0.75$ because our line of sight is approximately aligned with the shocked region. Near $\phi = 0.0$ and $\phi = 0.5$, our line of sight forms an angle $i \simeq 72°$ with the plane of the interaction region and the distribution of the radial velocities of the particles should then be narrower.

Similarly it also explains that absorption is dominating near $\phi = 0.0$ and $\phi = 0.5$ because we expect that the interaction region is (at least partiallly) occulted near conjunction phases. The difference between the two peaks near $\phi = 0.0$ and 0.5 might result from the difference of depth between the photometric eclipses of the system.

6. Conclusions

We have derived new orbital solutions and spectral types for several massive binaries of the young open cluster NGC 6231. A complete orbital solution for both components of the CPD $-41°7742$ system has been derived for the first time. From previous ROSAT PSPC observations, we show that the studied systems are X-ray overluminous, making them good colliding-wind candidates. Finally we show that the He II λ4686 and Hα lines of the HD 152248 system present phase-locked variations that are compatible with a colliding-wind model. The comparison of these results with the forthcoming XMM X-ray data will be extremely exciting. In fact, multiwavelength observations, including 'old-fashioned' optical spectroscopy, will provide an important complement to the

X-ray data and we hope that they will lead us towards a better understanding of the colliding-wind process.

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References

Baume, G., Vázquez, R.A., & Feinstein, A. 1999, A&AS, 137, 233

Berghöfer, T.W., Schmitt, J.H.M.M., Danner, R., & Cassinelli, J.P. 1997, A&A, 322, 167

Conti, P.S. 1973, ApJ, 179, 181

Corcoran, M.F. 1996, RevMexAA Conf., 5, 54

Corcoran, M.F. 1999, RevMexAA Conf., 8, 131

Lafler, J., & Kinman, T.D. 1965, ApJS, 11, 216

Mathys, G. 1988, A&AS, 76, 427

Mathys, G. 1989, A&AS, 81, 237

Mayer, P., Lorenz, R., & Drechsel, H. 1992, IBVS, 3765, 1

Penny, L.R., Gies, D.R., & Bagnuolo, W.G.Jr. 1999, ApJ, 518, 450

Rauw, G., Sana, H., Gosset, E., Vreux, J.-M., Jehin, E., & Parmentier, G. 2000, A&A, in press

Raymond, J.C., & Smith, B.W. 1977, ApJS, 35, 419

Stevens, I.R., Blondin, J.M., & Pollock, A.M.T. 1992, ApJ, 386, 265

Stickland, D.J., Lloyd, C., Penny, L.R., Gies, D.R., & Bagnuolo, W.G.Jr. 1996, The Observatory, 116, 226

Wolfe, R.H.Jr., Horak, H.G., & Storer, N.W. 1967, in Modern Astrophysics, ed. M. Hack (New York: Gordon—Breach), 251

Relaxing outside the hotel before the next onslaught: Sean, Orsola, Stan, Debra, Ken and Hugues

Discussion

Tony Marston: What did you mean when you talked about the over-luminosity of binary systems compared to single O-stars?

Gregor Rauw: I just wanted to point out that the *bolometric* luminosity is larger than expected for a single O star.

Tony Marston: Yes, but there are two O stars there and the over-luminosity is a factor of two.

Stan Owocki: Yes but he is talking about the bolometric luminosity for both stars.

Tony Marston: Oh, OK.

Tony Moffat: Even worse than that is that a factor of two is in the noise so what does it mean really, for one individual case?

Mike Corcoran: I think one reason to believe the over-luminosity though is that if you look at HD152248, which I presented at the La Plata conference, the X-ray emission is clearly phase-variable in exactly the way you would expect; that is, you see an emission peak at quadrature.

Stan Owocki: By how much?

Mike Corcoran: A factor of two!

Stan Owocki: Yes. [Laughter.]

Mike Corcoran: It is not noise.

Allan Willis: Just a comment on that point. Did you see any change in the hardness ratio in this factor-of-two variation?

Hugues Sana: I looked at the X-ray data and it is very difficult to see any variation of the hardness ratio because the signal-to-noise of the data are not so good.

Allan Willis: My original question was related to the XMM observations, which are going to be fantastic. How is the scheduling going to be organized? Is it going to be around the orbit?

Hugues Sana: It is organized to match best the period of HD152248.

Allan Willis: Will it be separate observations?

Hugues Sana: Yes, we have six times 30 kilo-seconds for this system.

Allan Willis: Keep your eye on the schedulers! [Laughter.] Sometimes they just think it's one observation.

Andy Pollock: It looked interesting that you detected five binaries and they all have periods between 4.2 and 5.8 days. Is that interesting?

Hugues Sana: Well, we observed three times a week over two years and we mainly obtained one spectrum per object per night. So it might result in a selection effect on the detected systems.

Sergey Marchenko: Is the Hα emission *all* coming from the wind-wind collision zone or is there something from the wind?

Hugues Sana: We assumed that it is coming all from the collision region but it is very difficult to disentangle the absorption and the emission components.

Mike Corcoran: I just wanted to draw attention to WR79 and also make an appeal. It should be a good colliding-wind system I think but it is a very weak X-ray source. It is a peculiar case because it's almost undetected even by a deep ROSAT pointing . Either the X-rays are very hard or it is a very weak source.

Aha, so it **was** an LBV inside the paper bag! (see p. 171)