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X-shooter, NACO, and AMBER observations of the LBV Pistol Star *

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Abstract We present multi-instrument and multi-wavelength observations of the famous LBV star Pistol Star. These observations are part of a larger program on early O stars at different metallicities. The Pistol Star has been claimed to be one of the most massive star known, with 250 solar masses. We present preliminary results based on X-shooter spectra, as well as observations performed with the VLTI-AMBER and the VLT-NACO adaptive optics. The X-shooter spectrograph provides simultaneously a spectrum from the UV to the K-band with a resolving power of $\sim$15000. The preliminary results obtained indicate that Pistol Star has similar properties to η Car, including shells of matter, but is also a binary.

1 Introduction

LBV stars are exceptional transition objects in the stellar evolution of massive stars. η Car is the emblematic object of this category. It is now postulated that this kind of star could be a possible aborted supernova (SN). In all cases, they present a special interest for the stellar evolution theory and models because they have strong winds, and asymmetries in their structure, are very luminous at the Eddington limit or above. According to Groh et al. (2009), 2 kinds of "LBV-phases" could exist: the strong variable LBV with S-Dor variability that could be near critical rotators, and the group of dormant LBV with less variability like P-Cygni. Moreover, the progenitors of various supernova

*Based on ESO runs 85.D-0182A, 085.D-0625AC

were LBVs, including SN2006jc (Foley et al. 2007) and SN2006gy (Smith et al. 2007). This direct evolution from LBV to SN, without passing through the WR phase is not understood yet (Smith et al. 2007) but could lead to the ultra-powerful pair-instability SN.

2 Observations

The observations are spread over several months: 12/2009, 05-06-09/2010. Early O stars were observed with X-shooter: BRRG56, [ELS2006]N11-026, [ELS2006]N11-029 in the LMC. These stars were selected as they are expected to be among the earliest O stars in the LMC. BRRG56 is classified as an O2 star. They show few absorption lines and several emission lines. In the Galaxy, the brightest known O star [BSP2001]8 (Martins et al. 2008) and one of the most massive claimed stars, the LBV Pistol Star with 250 $M_{\odot}$, were observed with X-shooter. In addition, the Pistol Star was partially observed with the VLTI-AMBER using the UTs and with the VLT NACO-AO assisted imager.

2.1 Brief description of instruments

Three instruments were used to probe the environment of Pistol Star at different spatial scales, to study the nature of Pistol Star itself, and to obtain some parameters/properties of its surrounding nebula.

The VLT-X-shooter (D'Odorico et al. 2006): it is the first 2nd generation instrument and is a very efficient echelle spectrograph. It has a large simultaneous wavelength coverage from the near UV to the K-band, with three different arms. The UVB arm allows to make observations in the $\lambda\lambda$ 290 to 600nm range, the VIS arm from $\lambda\lambda$ 535 to 1050nm, and the NIR arm from $\lambda\lambda$ 980 to 2500nm. The resolving power of each arm is defined by the slits used, in the UVB arm from 3300 to 9100, in the VIS arm from 5400 to 19000, in the NIR arm from 3500 to 11500.

The VLT-NACO (Lenzen et al. 2003, Rousset et al. 2003) is an adaptive optics assisted imager in the wavelength range 1-5 microns. It allows the scan of spatial scales from several arcseconds down to 20-15mas. The observations were performed with the K, Lp, and NB4 filters.

The VLTI-AMBER (Petrov et al. 2007) is a near-infrared, multi-beam interferometric instrument, that combines up to 3 telescopes for the VLTI at ESO, sensitive to spatial scales from 20 to 3 mas. The observations of Pistol Star were challenging because this star (K$\sim$8 at the time of the observation) is the faintest object observed at the VLTI with a UTs triplet and at the limit of AMBER capabilities, while at this magnitude the fringe tracker FINITO cannot be used.

2.2 VLT-X-shooter spectroscopy for the Pistol Star

This section presents very preliminary results coming from X-shooter spectra. The data reduction and analysis are still in progress. The resolutions used are: R = 4000 in the UVB arm, R = 6700 in the VIS arm, and R = 11500 in the NIR arm. Two exposures of 3000s were taken in the UVB and VIS arms, and about 100 exposures of 50s in the NIR arm. A representative set of UVB, VIS, and NIR frames is shown in Fig. 1. The first quick-look at the spectra indicates that:

- in the last 2 orders of the UVB arm, a very faint object of V$\sim$27 is detected. Looking at the NACO image it could correspond to an object at 2.8" west-side of Pistol Star. This object will provide information about the extinction in that part of the sky.

- in the VIS arm, Pistol Star appears in the last 5 red orders, i.e at the 770-1050nm wavelength range. It is not visible in the bluest orders, because Pistol Star is highly extincted by its circumstellar nebulosity. Up to now no spectrum bluer than 1000nm has been obtained of Pistol Star. The study of the available lines in that range will help us to better understand/classify the star by providing more

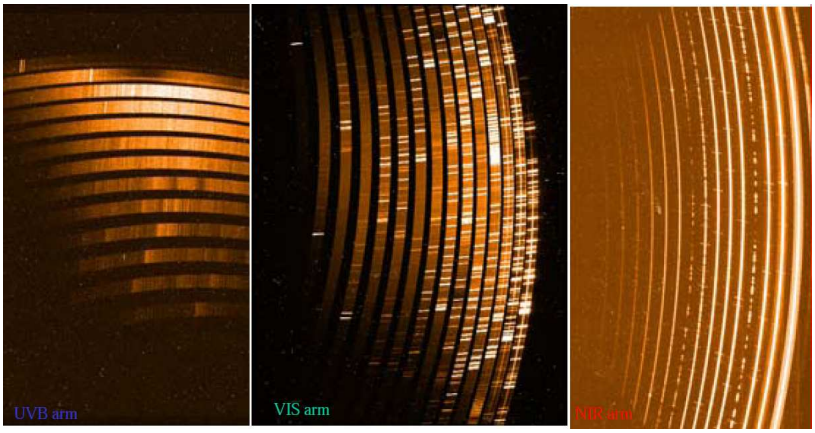

Figure 1: Snapshots of the 3 X-shooter arms of Pistol Star observations. Left: UVB arm (290-600nm), middle: VIS arm (525-1050nm), right: NIR arm (980-2500nm). One can see the spectra of Pistol Star mainly in the NIR arm as well as in the reddest orders of the VIS arm. Another very faint object can be seen in the UVB arm.

constraints on physical parameters such as the temperature. Some of the lines seem to show a double-peak profile. This could be related to a potential binarity or shell signatures. Some other lines also show P-Cygni profile.

- in the NIR arm, Pistol Star is easily seen in each order, and in the VIS arm, there are emission lines due to the nebulosity surrounding the central star. Some of them, such as Brγ show P-Cygni profile with a faint blue absorption component and a red strong emission peak corresponding to the shell of ejected matter. A small extract of the NIR spectrum near the Brγ line with lines of [Fe II], Fe II, Mg II, Na I and He I, is shown in Fig. 2. Several lines seem also to show a double-peaked structure indicating that possibly there is spherical expansion of the matter (as already reported by Figer et al. 1999) or/and a companion. Moreover, the EW of the lines are variable when they are compared with Figer et al. (1999) measurements, indicating a possible evidence of a variability cycle of Pistol Star. Is it related to the shells and matter-ejection, pulsations, and/or to a companion? Further observations and the study of the available lines in the VIS and NIR arms will help to obtain more information on the star(s) and on the circumstellar material/shell(s).

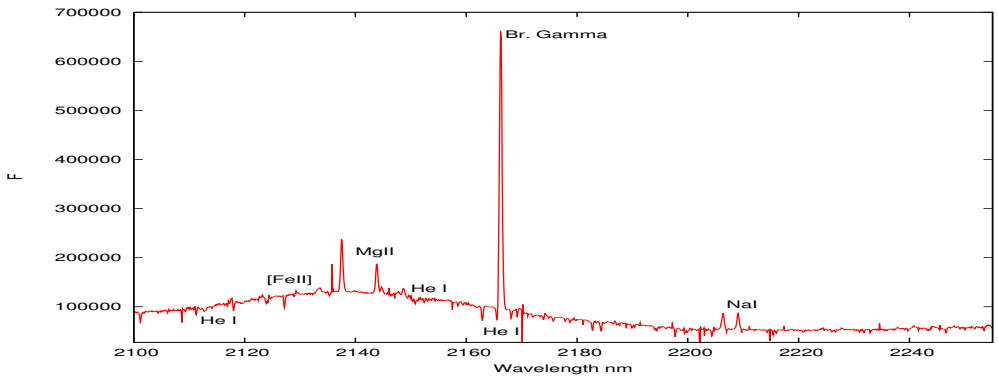

Figure 2: Small extract of the X-shooter NIR spectrum of Pistol Star in the region close to the Brγ line. One can see the P-Cygni profile of the Brγ line.

2.3 Pistol Star and the surrounding stars with the adaptive optics NACO.

The NACO images in Fig. 3 clearly show that the 2 "B" and "C" 2MASS stars are 2 groups of stars within few arcseconds. The "E" star corresponds to the Mira V4644 Sgr and seems to be surrounded by a shell. The "D" star corresponds to WR 102e. The "A" star corresponds to Pistol Star. The star in the right top of the bottom part of Fig. 3 shows the NACO PSF. One can see several stars close to the central system of Pistol Star at less than 0.4". Moreover it seems that Pistol Star is surrounded by different concentric shells of matter. The largest one roughly measures 0.07pc (Pistol Star is at least at 7.7kpc). As explained in the previous section, the faint spectroscopic double-peaked profile could correspond to the ringlike signature of spherical expansion.

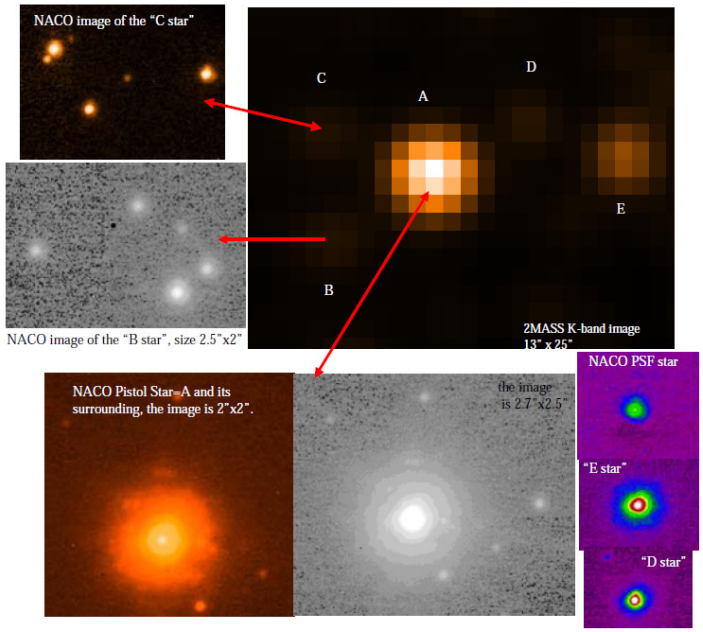

Figure 3: NACO observations of Pistol Star and the stars in its vicinity. The top panel shows the 2MASS image and extracts of the NACO K band image. The bottom panel shows Pistol Star with inner small shells of matter in K-band. The right column shows different stars including a PSF reference star.

2.4 Possible binarity of Pistol Star (VLTI-AMBER)

With these VLTI-AMBER observations we were able to scan smaller scales than with NACO. Moreover, the NACO, VLTI-AMBER, and X-shooter observations have the K-band in common that will be used to better understand/constrain the system of Pistol Star. From the VLTI-AMBER observations in K-band (the triplet UT-2-3-4 was used), it rises that there is a departure from single-star morphology. A companion of the Pistol Star has been detected with a rough separation of 10-50 mas ($\sim$80-400 AU). The visibility measurements are the best fitted by a model of a companion, while other models (disks, knot of the nebulosity) are not able to properly fit them. Figure 4 shows the corresponding $\chi 2$ map of the visibility of the VLTI-AMBER observations indicating in the framework of a companion-model, the companion position. The data reduction and analysis are in progress but this result suggests that as in the η Car case (Weigelt et al. 2007), the evolution and the understanding of the Pistol Star structure must go through a binary channel. Moreover, the VLTI observations suggest a minimum orbital period of several decades (unless, as in η Car, the eccentricity is large so that the

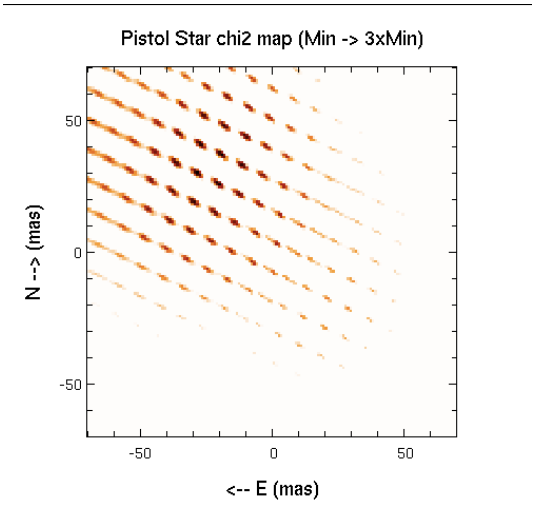

Figure 4: $\chi 2$ map of AMBER observations showing the possible positions of the Pistol Star companion. Pistol Star A is at (0,0).

current separation might not be representative of the orbit dimension at all). Long term monitoring of the system must be done in order to confirm the presence of the companion, to determine its location and its orbit to check its gravitational link, and finally determine the masses of the stars.

3 Conclusion

Combining multi-wavelength and multi-technique observations, one can better probe the nature of LBVs and better understand their properties. In the case of Pistol Star, it was found that it has a spectroscopic variability, that there are small inner shells of matter, and that the star is a possible binary. Together, these properties combine to make the Pistol Star a twin of the LBV η Car. A more detailed study will be published in a forthcoming article.

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