SPECTROSCOPY OF THE PISTOL AND QUINTUPLET STARS IN THE GALACTIC CENTRE*

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ABSTRACT

We present initial results of a spectroscopic study of the Pistol and of the cocoon stars in the Quintuplet Cluster. From ISOCAM CVF 5—17 μm spectroscopy of the field of the Pistol Star, we have discovered a nearly spherical shell of hot dust surrounding this star, a probable LBV. This shell is most prominent at $\lambda \gtrsim 12\,\mu$m, and its morphology clearly indicates that the shell is stellar ejecta. Emission line images show that most of the ionised material is along the northern border of this shell, and its morphology is very similar to that of the Pistol H II region (Yusef-Zadeh & Morris, 1987). We thus confirm that the ionisation comes from very hot stars in the core of the Quintuplet Cluster. An SWS spectrum of the Pistol Nebula indicates a harder ionising radiation than could be provided by the Pistol Star, but which is consistent with ionisation from Wolf-Rayet stars in the Quintuplet Cluster. The CVF 5—17 μm spectra of the cocoon stars in the Quintuplet do not show any emission feature that could help elucidate their nature.

Key words: ISO, Galactic Centre, Quintuplet, Pistol, LBVs

1. INTRODUCTION

The Quintuplet Cluster is one of the few young clusters known in the vicinity of the Galactic Centre. It took its name from five very luminous, $\sim 10^5\,L_\odot$ sources with very cool, 600—1200 K, energy distributions (e.g. Moneti, Glass, and Moorwood 1994, MGM94), henceforth the *cocoon* stars, and it is now known to contain several dozen hot stars (Figer, McLean, & Morris 1999, FMM99, and references therein for a detailed background) including several Wolf-Rayet stars, several OB supergiants, and at least one and probably two luminous blue variables (LBV; Figer et al. 1998, and references therein). One of these is located about 20 arcsec south of the cluster core and is now known as the *Pistol* star because of its location at the center of curvature of the G0.15–0.05 H II region (Yusef-Zadeh & Morris 1987), known as the *Pistol* because of its shape, and itself located half way between the cluster core and the Pistol star. The Pistol H II region was also detected in Br-γ (MGM), and was imaged in [Ar II] (Nagata et al. 1996) and in Pa-α (Figer et al. 1999), confirming its thermal origin (as opposed to the non-thermal origin of the radio filaments which appear to cross it, Yusef-Zadeh & Morris 1987).

Early studies of the Pistol star indicated it had extremely high luminosity ($2\times10^6 L_\odot$, Figer, McLean & Morris 1995, FMM95, and $10^7 L_\odot$ Cotera et al. 1996). There have also been suggestions that the Pistol Star could be photoionising the Pistol H II region (e.g. Cotera et al. 1996), while FMM95 suggested that the H II region is material ejected from the LBV which is photoionsed by the hot stars in the Quintuplet Cluster. By modeling its IR spectral energy distribution (SED) and its IR line profiles, Figer et al. (1998) constrained the Pistol Star's luminosity to two classes of models, one with $L_* \approx 4\times10^6\,L_\odot$ and $T_{\rm eff} \approx 14,000$ K, and the second with $L_* \approx 15\times10^6\,L_\odot$ and $T_{\rm eff} \approx 21,000$ K. What remained unclear was why the ejecta was only seen to the north of the star.

The nature of the cocoon stars remains mysterious. Okuda et al. 1990 and MGM94 suggested they might be star-forming cocoons similar to BN or AFGL2591. FMM99 favour extremely dusty WC stars, but also suggests that they could form a new class of objects. Glass et al. (1999) report slight variability of two of the five cocoon stars at 2.2 μm, possibly inclining the balance toward the evolved nature of these stars. To date, no emission feature has been detected toward these stars that could help elucidate their nature, and the only absorption features are due to silicates and ices (Nagata et al. 1996), all of which are believed to be of interstellar origin.

*ISO is an ESA project with instruments funded by ESA Member States (especially the PI countries: France, Germany, the Netherlands and the United Kingdom) and with the participation of ISAS and NASA.

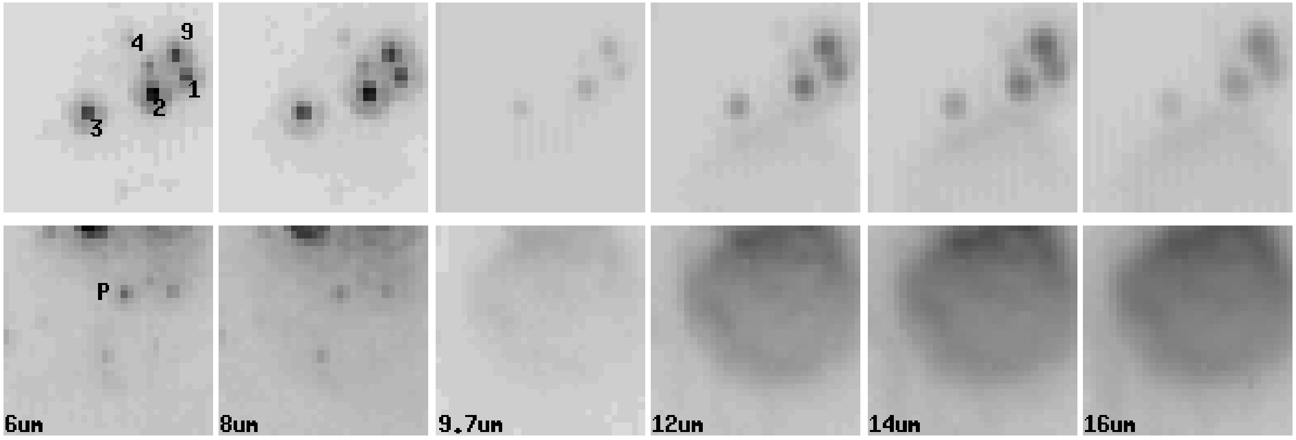

Figure 1. Continuum images of the Quintuplet Cluster (top) and of the Pistol Nebula (bottom). North is up, and east is to the left. The vertical stripes in the Quintuplet images are due to incomplete dark subtraction at the 0.28 sec on-chip integration time. Wavelengths corresponding to each frame are marked, and the Quintuplet and Pistol stars are identified.

2. OBSERVATIONS AND RESULTS

We have obtained ISOCAM-CVF scans of the Pistol and of the Quintuplet fields, covering the 5.0—17.1 μm spectral range. All scans were obtained with a pixel FOV of 1.5 arcsec, and the integration time was ~ 30 sec per CVF position, using the 2.1 and the 0.28 sec on-chip integration time on the Pistol and on the Quintuplet, respectively. Data reduction was performed with the CAM Interactive Analysis (CIA) package[1], and followed the standard steps of (i) dark subtraction, (ii) removal of cosmic ray events, (iii) averaging all valid images obtained at a given CVF position, (iv) flatfielding the results using library flats, (v) converting the average signal to physical units using standard conversion factors, originally derived from several standard stars. No transient correction was applied to the data presented here; given the brightness of the sources, the transient correction is very minor, below a few percent, and for the discussion presented here these deviations are not important.

Figure 1 shows a composite of continuum images of the Quintuplet and of the Pistol. They are scaled so that the intensities are proportional to the observed energy density, $\lambda F(\lambda)$, with the scaling for the Pistol being $5\times$ stronger than for the brighter Quintuplet Stars. Both datasets clearly reveal the deep 9.7 μm silicate absorption feature. The images of the Quintuplet Cluster are dominated by the cocoon stars, whose identification, following MGM94, is shown. Since images are diffraction limited, the FWHM of the images can be seen to increase with wavelength, and the first Airy ring can also be recognised. Also, the brightest stars at short wavelengths are no longer so at long wavelengths, showing their different colour temperatures. The Pistol Star is the point source located just above centre in the Pistol field, marked with a "P". It is most clearly visible at short wavelengths, where other stars are also detected. The peak at the top edge of the frame corresponds to star no. 3 in the Quintuplet. Beyond the silicate feature the Pistol Star is lost in a nearly spherical centered on the Pistol star itself. The diameter of this Pistol Nebula is ~ 1.5 pc.

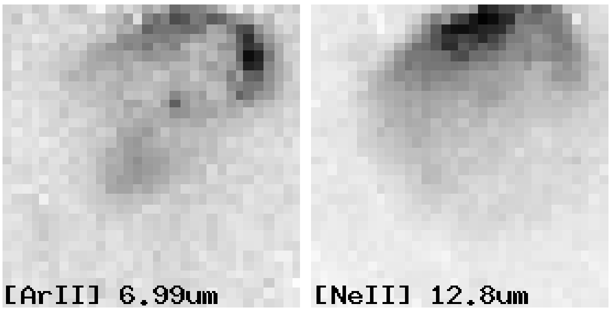

Figure 2. Line images of the Pistol Nebula.

Raw spectra extracted from the Pistol data cube show PAH emission at 6.2, 7.7, and 8.6 and 11.3 μm, and the fine structure lines of [ArII] 7.0 μm, [NeII] 12.8 μm, and [NeIII] 15.4 μm. Line images reveal that the PAH emission is uniform over the field, thus indicating that it is interstellar rather than local to the nebula, while the forbidden line emission is not. The spatial distribution of [ArII] and [NeII] is shown in Figure 2. The morphologies are similar, thought not identical, and they are also similar to the Pistol HII region (Yusef-Zadeh and Morris, 1987, see also Figer et al. 1998). Energy distributions of the northern, central, and southern parts of the Pistol Nebula are shown in Figure 3, together with the energy distributions of four of the cocoon stars. Photometry of these stars was obtained by measuring the flux within a 3 arcsec aperture and correcting for the aperture size using measurements of single stars. The Pistol Nebula spectra were extracted using 7×17 pixel synthetic aperture, and were normalised by the number of pixels. The background was determined from the southernmost region of the field, and subtracted. It

[1] CIA is a joint development by the ESA Astrophysics Division and the ISOCAM consortium, led by the ISOCAM PI, C. Cesarsky, Direction des Sciences de la Matière, C.E.A., France

is clear from the energy distributions that the silicate absorption is much deeper in the cocoon stars than in the Pistol Nebula. Table 1 lists the measured optical depths, $\tau_{\rm sil}$, relative to a power-law continuum fitted through the spectral points at 8 and 13 μm. For comparison, from the Lutz et al. (1996) SWS spectrum of the Galactic Centre we derive $\tau_{\rm sil} = 2.0$. The difference in the depth of the feature in the Quintuplet Stars and in the Pistol is consistent with the results of Nagata et al. (1993).

Table 1. Silicate feature optical depths

Source	$\tau_{\rm sil}$
Q1	2.60
Q2	2.51
Q3	2.38
Q9	2.52
north	1.40
centre	1.32
south	1.08

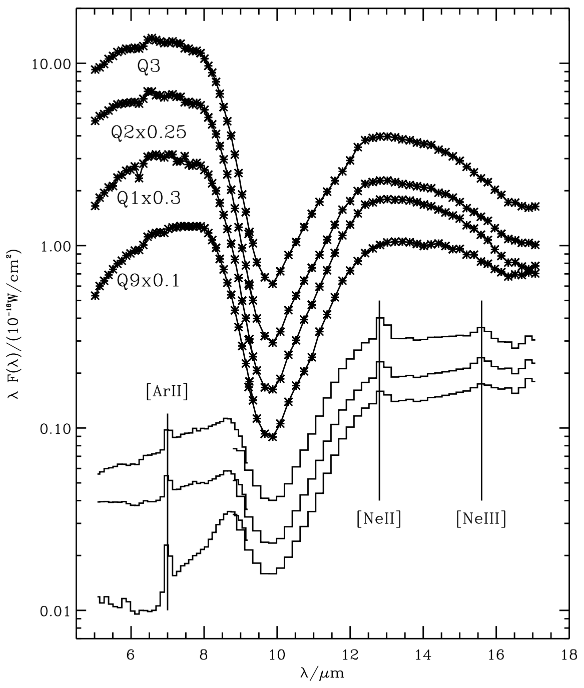

Figure 3. Spectral energy distributions of the northern, central, and southern part of the Pistol Nebula, shown with arbitrary normalisation, and of the cocoon stars.

An SWS spectrum covering the 2.3—47 μm range was obtained with the Pistol Star centered in the aperture. The AOT1-speed 4 mode was used, for a total integration time of $\sim$ 2 hrs. Pipeline-processed data was cleaned by removing data from noisy detectors, normalising each scan to the average of the complete dataset, and rebinning to a resolution of 1,000. This result was then defringed by finding and removing the strongest sinusoidal components. The final spectrum is shown in Figure 4; it shows a wealth of fine structure lines, many hydrogen recombination lines, and the standard absorption features of interstellar origin (silicates at 9.7 μm and 18 μm, water ice at 2.9 μm, hydrocarbons at 3.4 μm, and CO_2 ice at 4.3 μm, though the latter are not obvious in the representation given in Figure 4, which emphasises the emission lines. Preliminary analysis indicates that at $\lambda \lesssim 5\,\mu$m the continuum and the lines come primarily from the Pistol Star and its wind, while at longer wavelength they come primarily from the hot dust and the ionised gas in the HII region. A detailed analysis of the lines is in progress and will be presented in a future paper.

3. DISCUSSION

The discovery of a spherical nebula around the Pistol Star is the main result of this work presented at this workshop: our observations in the thermal IR have revealed the full shell of ejecta symmetrically distributed around the Pistol Star. Up until now, only the ionized part of the Pistol Nebula had been known, originally from radio continuum observations (Yusef-Zadeh and Morris, 1987), but subsequently also from near IR spectroscopy (see the Introduction). Many LBVs are known to be surrounded by shells of ejecta which is seen in reflection in the optical and near infrared (Nota et al. 1995) and via its thermal dust emission in the mid infrared (Trams et al. 1996, 1999). The size of the Pistol Nebula is comparable to that of other LBVs (Nota et al. 1995, Table 1), though unlike other LBVs, the nebular structure appears more as a full sphere than as a shell. Since the ejecta is not uniformly ionised, the ionisation probably does not come from the Pistol Star, which consequently must be relatively cool. This argues in favour of the cooler and lower luminosity class of models proposed by Figer et al. 1998. More likely, the ionisation come from other hot stars in the Quintuplet Cluster (FMM95, FMM99), of which there are several north of the ionised ridge. Other cluster stars (no. 76, 151, and 157 in FMM99) are located over the Pistol Nebula in projection, and two of these (no. 7 and 157) may be physically inside the nebula and could be responsible for the details of the structures seen in the ionised line images.

The relative strength of the high excitation lines in the SWS spectrum also indicates that the ionisation must come from stars stars much hotter than the Pistol Star. The ratios of [SIV]/[SIII], of [ArIII]/[ArII], and of [NeIII]/[NeII] in the Pistol spectrum are much stronger than in the Galactic Centre spectrum obtained by Lutz et al. (1996), from which these authors derive an average effective temperature of the ionising sources of 35,000 K. We deduce that at least some of the stars ionising the Pistol material must be hotter than 35,000 K, and the Wolf-Rayet stars in the Quintuplet Cluster are clearly indicated as the ionising stars.

The above scenario assumes that the Pistol Star and the cocoon stars are all members of the Quintuplet Cluster, though strictly speaking, this scenario involves only the Pistol Star and the hot stars in the cluster, and not the cocoon stars. In this context, the low silicate absorption optical depth of the the Pistol Nebula compared to the cocoon stars is puzzling. Either there is a steep gradient in extinction over the

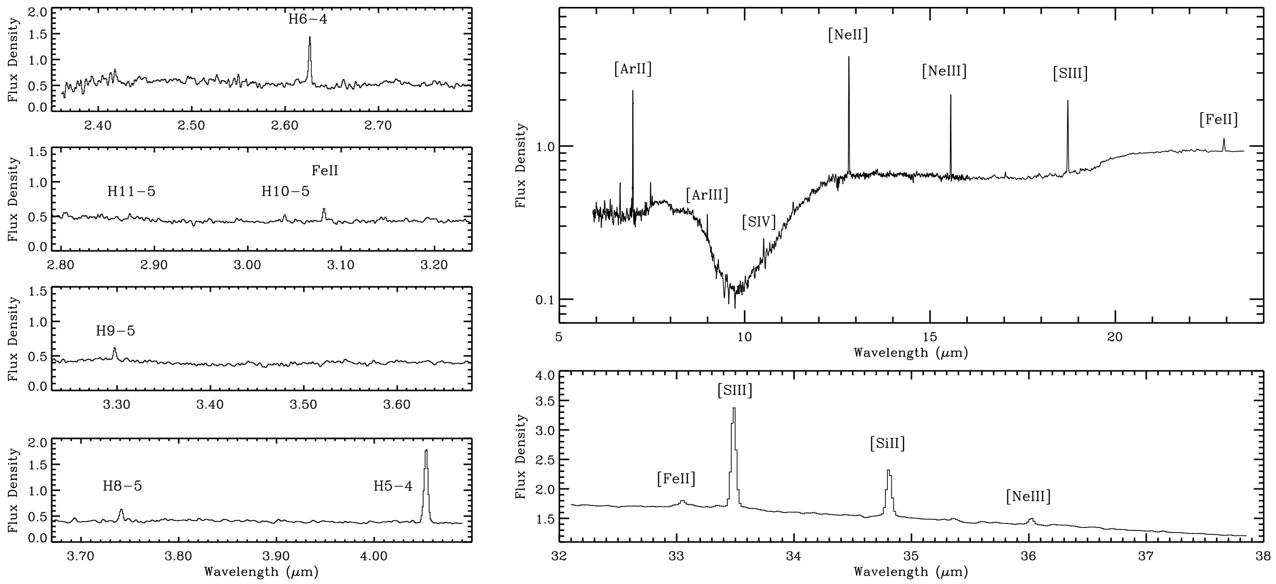

Figure 4. SWS spectrum of the Pistol Nebula. Different parts of the spectrum are plotted separately for clarity. The flux density is in units of $10^{-16}\mathrm{W/cm^2/\mu m}$.

cluster, decreasing rapidly from north to south, or the extinction is spatially uniform, in which case the cocoon stars and the Pistol Star are at different distances along the line of sight. Alternatively, the silicate absorption of the cocoon stars is not entirely interstellar, but it is partly intrinsic. Figer et al. (1998) reviewed extinction estimates to the Quintuplet Cluster. They estimate $A_K = 3.28$ and adopt the Rieke, Rieke and Paul (1989) reddening law as the one that best characterises the reddening towards the hot stars in the Quintuplet. This gives $A_V = 29 \pm 2$ to the hot stars, and is an appropriate value for the Pistol Star, placing the whole group physically close to the Galactic Centre. Using $A_V = 29$, we obtain $A_V/\tau_{sil} = 20.5$ for the Pistol Nebula, a value comparable to that found by Roche and Aitken (1984) for nearby Wolf-Rayet stars and B supergiants. At the same time, the same A_V gives $A_V/\tau_{sil} = 11.6$ for the cocoon stars, a value more typical of sources in the Galactic Centre (Rieke and Lebofsky 1985). We do not offer a solution to this problem at this time.

In conclusion, we have solved one dilemma by discovering the full shell of ejecta around the Pistol Star, thus further confirming its LBV nature, but we have opened a new one by finding that τ_{sil} varies drastically between the Pistol Star/Nebula and the cocoon stars. These are only the first results from this data set; further analysis is in progress, and in an upcoming paper we will present a detailed analysis of the emission lines, which we will use to put constraints on the nature of the ionising radiation and of the extinction.

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