Chemical abundances in the protoplanetary disc LV 2 (Orion): clues to the causes of the abundance anomaly in H\(\text{II}\) regions

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ABSTRACT

Optical integral field spectroscopy of the archetype protoplanetary disc LV 2 in the Orion nebula is presented, taken with the Very Large Telescope (VLT) FLAMES/Argus fibre array. The detection of recombination lines (RLs) of C\(\text{II}\) and O\(\text{II}\) from this class of objects is reported, and the lines are utilized as abundance diagnostics. The study is complemented with the analysis of Hubble Space Telescope (HST) Faint Object Spectrograph ultraviolet and optical spectra of the target contained within the Argus field of view. By subtracting the local nebula background the intrinsic spectrum of the proplyd is obtained and its elemental composition is derived for the first time. The proplyd is found to be overabundant in carbon, oxygen and neon compared to the Orion nebula and the Sun.

The simultaneous coverage over LV 2 of the C\(\text{II}\) \(\lambda 1908\) and [O\(\text{II}\)] \(\lambda 5007\) collisionally excited lines (CELs) and C\(\text{II}\) and O\(\text{II}\) RLs has enabled us to measure the abundances of C\(^{2+}\) and O\(^{2+}\) for LV 2 with both sets of lines. The two methods yield consistent results for the intrinsic proplyd spectrum, but not for the proplyd spectrum contaminated by the generic nebula spectrum, thus providing one example where the long-standing abundance anomaly plaguing metallicity studies of H\(\text{II}\) regions has been resolved. These results would indicate that the standard forbidden-line methods used in the derivation of light metal abundances in H\(\text{II}\) regions in our own and other galaxies underestimate the true gas metallicity.

Key words: planets and satellites: general – protoplanetary discs – stars: pre-main-sequence – stars: protostars – ISM: abundances – H\(\text{II}\) regions – ISM: individual objects: LV2 – ISM: individual objects: 167−317 – ISM: individual objects: Orion nebula.
The observed data cubes are subject to atmospheric refraction as a function of wavelength, known as differential atmospheric refraction (DAR). The direction of DAR is along the parallactic angle at which the observation is made. The six wavelength- and flux-calibrated data cubes for Giraffe low-resolution modes LR1 to LR6 were corrected for this effect using the algorithm outlined by Walsh & Roy (1990); using the airmass information this procedure calculates fractional pixel shifts for each monochromatic slice of a cube relative to a fiducial wavelength (e.g. a strong emission line), shifts each slice with respect to the orientation of the slit on the sky and the parallactic angle and recombines the DAR-corrected data cube. The wavelength overlap of each LR setting does not always allow a strong (e.g. Hα or He i) line to be used to align each data cube to correct for pointing differences between different grating set-ups. The LV 2 proplyd was the only compact feature that could be used to align the images across the Argus field. The LR1, LR2, LR3 and LR6 cubes were aligned using, respectively, the He i, Hγ, Hβ and Hα lines; the LR5 cube was aligned using He α using contemporaneous exposures of various lines; the LR5 cube was aligned using He α.

Of equal importance is to examine what, if any, the role of proplyds might be in the context of the long-standing abundance anomaly affecting studies of galactic and extragalactic H II regions, whereby larger abundances are derived from the optical recombination lines (RLs) than from the collisionally excited lines (CELs) of oxygen and carbon ions (e.g. Peimbert, Storey & Torres-Peimbert 1993; Peimbert 2003; Tsamis et al. 2003a; Esteban et al. 2004; García-Rojas et al. 2004; Tsamis & Péquignot 2005; Mesa-Delgado et al. 2008, 2010; Ercolano 2009; Esteban et al. 2009). Here the first detailed study of a proplyd geared towards tackling these open issues is presented.

2 OBSERVATIONS AND REDUCTIONS

Integral field spectroscopy of LV 2 was performed on the 8.2-m VLT/UT2 Kueyen during period 78 with the FLAMES Giraffe Argus array. A description of the instrument can be found in Pasquini et al. (2002). A field of view of 6.6 × 4.2 arcsec$^2$ was used yielding 297 positional spectra in the 3620–7184 Å range from six partially overlapping grating settings. The size of the spatial resolution element was 0.31 × 0.31 arcsec$^2$, corresponding to 123 × 123 au$^2$ at the distance to M 42 (412 pc; Reid et al. 2009). The location of the Argus field on the Trapezium region of M42 is shown in Fig. 1. The Argus data were reduced with the girBLDRS pipeline developed by the Geneva Observatory which includes the cosmic ray removal, the flat-fielding and the wavelength calibration via Th–Ar lamp exposures (Blecha & Simond 2004). The flux calibration was done within IRAF using contemporaneous exposures of several spectrophotometric standards for the grating settings [EG 21 (LR1), Feige 110 (LR2, LR3), LTT 7987 (LR4–6)]. Custom-made scripts were used to construct data cubes and spectral line maps, and a $\chi^2$ minimization routine was used to fit Gaussians to the emission lines (cf. Tsamis et al. 2008).

The observed data cubes are subject to atmospheric refraction as a function of wavelength, known as differential atmospheric refraction (DAR). The direction of DAR is along the parallactic angle at which the observation is made. The six wavelength- and flux-calibrated data cubes for Giraffe low-resolution modes LR1 to LR6 were corrected for this effect using the algorithm outlined by Walsh & Roy (1990); using the airmass information this procedure calculates fractional pixel shifts for each monochromatic slice of a cube relative to a fiducial wavelength (e.g. a strong emission line), shifts each slice with respect to the orientation of the slit on the sky and the parallactic angle and recombines the DAR-corrected data cube. The wavelength overlap of each LR setting does not always allow a strong (e.g. Hα or He i) line to be used to align each data cube to correct for pointing differences between different grating set-ups. The LV 2 proplyd was the only compact feature that could be used to align the images across the Argus field. The LR1, LR2, LR3 and LR6 cubes were aligned using, respectively, the He i, Hγ, Hβ and Hα lines; the LR5 cube was aligned using He i λ4876 by comparison with He i λ4471 from the LR2 cube. For the LR4 range (5015–5830 Å), a sum of the prominent (forbidden) lines – [N ii], [Cl iii] and [N ii] – was used to compare with Hβ to determine the shift. The shifts required to align all the cubes were generally about 0.25 spaxels (0.08 arcsec) except for the LR1 cube whose shift was...
larger (0.20 arcsec). A result of this process is that the corrected maps are no longer of identical extent, depending on the shifts applied, but are suitable for line ratio maps to be constructed that have fidelity on a spaxel-to-spaxel basis over their common imaged area.

LV 2 and its surroundings were also observed with the HST FOS in 1996 in programme 6034. The FOS Red detector (mode FOS/RD) was employed with five gratings giving a total coverage from 1590 to 8500 Å with overlap between each spectral range (Keyes et al. 1995). The 0.3 arcsec single circular aperture was used which projects to 0.26 arcsec on the sky in the aberrated HST beam. Five positions on and in the near vicinity of LV 2 were observed. The positions were established by relative astrometry on an HST WFPC2 Hα + [N II] image taken in programme 5085 (PI: C. R. O’Dell). Offsets were then specified from a star at 05h35m17s00, −05°23′34″ of 15th magnitude (in the V band) selected from the catalogue of Orion stars by Jones & Walker (1988). This star was centred in the FOS aperture with a series of acquisition peak-ups in successively smaller apertures down to the observing aperture and then the offsets, measured from this star to the observing positions on the WFPC2 image, were applied.

Three positions around LV 2 were observed: the peak of LV2 (called ‘core’), 0.6 arcsec south-west of the peak (called ‘tip’) and 1.0 arcsec north-east of the peak (called ‘tail’); see Fig. 1 for these aperture positions which are contained within the Argus field of view. In addition two further positions, on an [S II]-bright filamentary ‘ridge’ of emission (‘M42-filament’) and a background position 1.5 arcsec east of this filament (‘M42-background’), were observed; these fall outside the Argus field of view −55 arcsec south-west from its centre. Table 1 lists the respective exposure times of all the grating settings and positions. The standard pipeline reduction products were used for the FOS data and emission-line fluxes were determined by fitting Gaussians to the extracted 1D flux and error spectra.

### 3 ANALYSIS OF HST FOS DATA

The FOS spectra were used for the computation of the physical conditions and abundances of the targeted positions, and as a means to independently check the reliability of the FLAMES spectrophotometry for the overlapping LV 2 positions. Spectra of the LV 2 core and tail observations are shown in Fig. 2. In Table 2 we present the reddened fluxes for the strongest lines detected at each position, along with the electron densities and temperatures derived from standard diagnostic line ratios. The adopted logarithmic reddening coefficient, $c(H\beta)$, was obtained from the $H\alpha/H\beta$, $H\gamma/H\beta$ and $H\delta/H\beta$ flux ratios using the modified Cardelli, Clayton & Mathis (1989, hereafter CCM) law from Blagrave et al. (2007) with a total to selective extinction ratio $R_V = 5.5$ applicable to M42. Values of $c(H\beta)$ were also deduced from a comparison of the observed $[O II] \lambda 2470/\lambda 3720 + 30$ line ratio to the almost invariant theoretical value of 0.75 taken from Zeippen (1982) (Table 2). These measurements typically suffer from larger uncertainties than the Balmer decrement. It is also possible that stellar light scattered within the nebula selectively enhances the UV/blue lines (e.g. O’Dell & Harris 2010) leading to lower reddening deduced from the UV/red $[O II]$ ratio for the M42 filament and background positions than from the Balmer decrement; in view of this the $c(H\beta)$ values from [O II] were not used in this analysis.

Electron densities were derived from the $[S II] \lambda 6716/\lambda 6731$ doublet ratio and the $[O II] \lambda 3726/\lambda 2470$ ratio. The former diagnostic is not sensitive to densities $\gtrsim 10^3$ cm$^{-3}$, while the latter is sensitive up to a few $10^4$ cm$^{-3}$ (e.g. Osterbrock 1989). At the same time the $[O II]$ ratio is somewhat $T_e$-sensitive: typically, higher $[O II]$ densities are returned for lower temperatures. The temperature applicable to the $O^+$ zone was derived from the $[O III] \lambda 5007/\lambda 4363$ ratio. For each FOS position the mean $T_e([O II])$ is quoted in Table 2 with a range corresponding to an adopted upper and lower density boundary. Those boundaries were taken from the positions where the $[O II]$ and $[N II]$ curves cross the $[O II]$ curve on the $(T_e, N_e)$ diagnostic plane for the M42 filament and LV 2 tip and tail positions. The $[N II] \lambda 6554/\lambda 6584$ ratio, just like the $[O II] \lambda 3726/\lambda 2470$ ratio, is mostly density sensitive for these positions. For LV 2 core the upper density boundary was taken to be $10^6$ cm$^{-3}$ (see Section 4.2). The auroral $[N II] \lambda 5754$ and $[O II] \lambda 4363$ lines are not detected in the M42 background spectrum and hence $T_e$ is available for it.

### 4 ANALYSIS OF VLT ARGUS DATA

The FLAMES Argus data were used in two ways: to create spectral maps of LV 2 and its vicinity and to obtain summed spectra for various regions. The $(X = 14, Y = 22, \lambda)$ spectral cube was co-added spatially over spaxels (3–5, 7–10), (4–9, 11–15) and (4–11, 18–20) + (7–12, 4–5) + (11–12, 6–17) to yield ID spectra for three regions, respectively, encompassing the core, tail and local background of LV 2 ($X$ and $Y$ are, respectively, measured on the minor and major axes of the Argus array). These regional spectra were scaled to the same number of spaxels and then the background spectrum was subtracted from the other two so that pure proplyd spectra were obtained. The subtraction resulted in spectra of LV 2 that are free from both nebular (M42) and telluric emission; these will be hereafter called the core and tail spectra. To orientate the discussion, maps of LV 2 in several emission lines including $H\beta$ are shown

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1. These were computed using the code {	exttt{qnum}} developed at University College London.
in Fig. 3. These show the observed field without any background subtraction. A dereddened map of Hβ is shown in Fig. 4.

The proplyd is marginally resolved in the emission-line maps, with a FWHM of about 2.5 spaxels (0.78 arcsec). There is no conclusive evidence of this varying between H I and He I, O II, C II, [O III] or [Ne III]. However, at the longer wavelengths in the low-ionization lines [N II] λ6584 and [S II] λ6731 the contrast of LV 2 against the background is low and the FWHM may be larger. In these lines there is a strong ionization front feature extending across the field of view from NW to SE (seen also in Fig. 1); this could arise in the nebula background but could also partially be intrinsic emission from the tail itself. The form of the tail does not differ noticeably between Hβ, He I, [O III] or [Ne III] presenting a fan shape (as it does on the HST image of Fig. 1). The signal-to-noise ratio in the C II and O II RLs and [Fe III] is too low to say conclusively what the morphology of the tail is in these species. The extinction map shown in Fig. 3 is not smooth on a spaxel to spaxel basis and shows local maxima along the ridge of [S II] emission noted above and at the position of the proplyd core.

It is challenging to produce a complete VLT optical spectrum throughout the range covered by the six Giraffe gratings taking into account that the LR1, 2, 3 set-ups were observed on a different night from the LR4, 5, 6 set-ups and over slightly different atmospheric conditions. It was therefore deemed appropriate to use the FOS ‘M42-background’ observations as a benchmark to which the Balmer decrement of the co-added LV 2 background spectrum obtained by Argus (as defined above) was scaled. In this way the mean reddening obtained for the LV 2 background region is no longer a free parameter as it is equalized to 0.7 (from Table 2, third column). To achieve this, scaling factors of 1.070 and 0.833 were applied to the LR2 and LR6 spectra, respectively, while the LR1 spectrum was scaled to the LR2 spectrum using the H I λ3970 line common to both gratings. The LR3, 4 and 5 fluxes were left unscaled. The same scaling factors were then applied to the co-added LV 2 core and tail spectra whose reddening constants are considered to be free parameters.

### 4.1 Nebular reddening

Measured line fluxes and derived physical conditions are shown in Table 3 for the (background-subtracted) core and tail, as well as the background spectra. The ε(Hβ) reddening coefficients were derived...
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Table 2. Line fluxes and physical conditions of M42 and L2 positions from HST FOS data.a

|                  | M42 filament | M42 background | LV 2 tip | LV 2 core | LV 2 tail | LV 2 core – tail |
|------------------|--------------|----------------|----------|-----------|-----------|-----------------|
| c(Hβ)            | 0.77 ± 0.07  | 0.71 ± 0.07    | 0.59 ± 0.07 | 0.72 ± 0.02 | 0.68 ± 0.06 | 0.70 ± 0.02     |
| c(Hγ)            | 0.46 ± 0.14  | 0.49 ± 0.27    | 1.01 ± 0.12 | 0.65 ± 0.12 | 0.78 ± 0.31 | 0.70 ± 0.07     |
| F(Hγ)            | 0.385 ± 0.02 | 0.340 ± 0.02   | 1.10 ± 0.02 | 3.53 ± 0.04 | 0.593 ± 0.02 | 2.99 ± 0.04     |
| I([NII] λ1908)   | 16.0 ± 5.5   | 13.1 ± 8.7     | 42.4 ± 7.2 | 75.2 ± 5.8 | –         | 87.4 ± 7.0      |
| I([NII] λ2326)   | 40.6 ± 8.0   | 13.1 ± 8.5     | 21.5 ± 3.8 | 47.6 ± 4.3 | ≤0.510    | 55.2 ± 6.1      |
| I([OII] λ2470)   | 24.8 ± 4.4   | 12.4 ± 4.8     | 15.7 ± 2.3 | 34.9 ± 2.5 | 7.10 ± 3.80 | 39.4 ± 3.8       |
| I([OIII] λ3726+29) | 171 ± 5     | 143 ± 6       | 34.2 ± 1.6 | 17.2 ± 0.4 | 75.9 ± 3.1 | 8.92 ± 0.86     |
| I([NeIII] λ3869) | 12.7 ± 1.3   | 13.7 ± 2.0     | 43.8 ± 3.9 | 45.3 ± 0.9 | 30.6 ± 1.8 | 47.6 ± 2.1       |
| I(HeI λ4471)     | 3.70 ± 0.8   | 3.65 ± 1.13    | 4.69 ± 0.59 | 4.47 ± 0.30 | 4.34 ± 0.89 | 4.49 ± 0.39     |
| I([OII] λ4959)   | 68.4 ± 3.6   | 99.5 ± 4.8     | 144 ± 3   | 133 ± 1    | 121 ± 3   | 135 ± 2         |
| I(HeI λ5876)     | 10.7 ± 1.7   | 12.1 ± 2.1     | 13.7 ± 0.95 | 14.0 ± 0.5 | 13.5 ± 1.2 | 14.1 ± 0.6      |
| I([SII] λ6312)   | 1.07 ± 0.04  | –             | 1.47 ± 0.40 | 1.96 ± 0.25 | 3.18 ± 1.69 | 2.00 ± 0.35     |
| I([NII] λ6584)   | 104 ± 7      | 60.0 ± 6.8     | 18.3 ± 1.4 | 18.3 ± 0.8 | 41.6 ± 3.8 | 14.5 ± 1.0      |
| I(HeI λ6678)     | 3.22 ± 1.6   | 2.18 ± 1.04    | 3.29 ± 0.67 | 4.06 ± 0.39 | 3.64 ± 1.48 | 4.13 ± 0.45     |
| I([SIII] λ6731)  | 12.3 ± 2.6   | 2.06 ± 0.08    | 1.55 ± 0.44 | 0.512 ± 0.193 | 4.13 ± 1.52 | –                |
| I([ArIII] λ7135) | 8.73 ± 2.9   | 14.5 ± 3.0     | 41.4 ± 1.9 | 24.1 ± 1.5 | 15.6 ± 2.2 | 25.5 ± 1.9      |
| I([OIII] λ7320+30)| 25.6 ± 5.4 | 13.5 ± 4.1     | 40.8 ± 5.9 | 46.6 ± 2.5 | 11.2 ± 0.7 | 52.3 ± 3.5      |
| I([OIII] λ4959/4363) | 63.9 ± 6.3 | –              | 27.6 ± 3.0 | 17.4 ± 0.9 | 63.5 ± 21.4 | 15.7 ± 0.9      |
| I([NII] λ6584/5755) | 31.3 ± 8.6 | –              | 12.7 ± 1.7 | 4.22 ± 0.21 | 28.2 ± 11.2 | 3.03 ± 0.32     |
| I([SII] λ6731/6716) | 2.53 ± 1.06 | 1.75 ± 0.26    | 3.76 ± 1.68 | –         | 1.78 ± 1.54 | –                |
| N_e [cm⁻³]      | >2300        | 4300 ± 5500    | ≥10⁴     | –         | –         | –                |
| N_e [cm⁻³]      | >1.7×10⁴    | 1.1×10⁴       | 4.5×10⁴       | 2.0×10⁴      | 1.0×10⁴      | 6.6×10⁵        |
| N_e [cm⁻³]      | 6.5×10⁴     | 1.4×10⁴       | 5.7×10⁴       | 7.9×10⁴      | 1.0×10⁵      | 6.6×10⁵        |
| T_e [K]         | 8850 ± 250  | 10950 ± 550   | 10700 ± 1300 | 8950 ± 1250 | 9050 ± 650 |

a c(Hβ) in row 1 were deduced from the H I Balmer ratios, in row 2 from the [OII] λ14270/3720+30 ratio. The former were adopted; F(Hγ) values correspond to observed fluxes within a 0.26 arcsec diameter aperture (in units of 10⁻¹³ erg cm⁻² s⁻¹); I(λ) denotes dereddened intensities in units of H I β = 100; · denotes very uncertain value.

b Derived from the I(λ7326)/I(λ2470) ratio for T_e = T_e([OII]λ); for ‘M42 background’ 8400 K was adopted from the Argus background spectrum.

from a comparison of the relative fluxes of the Hz, Hβ, He, Hδ and He lines with their theoretical values from Storey & Hummer (1995); Hα was saturated over the core and so the line was not considered for this position. The Blagrave et al. (2007) modified CCM law with R_V = 5.5 was used as previously. Resulting mean reddening constants are 1.20 ± 0.04 from the Hβ line of SMC data and 1.20 ± 0.02 from the Hα line of SMC data at 9700 ± 300 K; ‘·’ denotes very uncertain value.

Electron densities and temperatures from the Argus data were derived from various diagnostics. In Figs 5 and 6 a group of curves is shown on the (T_e, N_e) diagnostic plane representing solutions corresponding to the observed line ratios from Table 3. It should be noted that these ratios are for the rest-velocity components of the lines in each case. For the background region T_e = 9700 ± 500 K is obtained for the singly ionized species and 8400 ± 200 K for all other species with N_e = 4700 ± 1400 cm⁻³. For the tail region T_e = 9700 ± 300 K and log[N_e (cm⁻³)] = 4.58±0.28 is adopted for all species. For the core region, which is expected to be very dense, both the [OIII] and especially the [NII] nebular to auroral ratios become more sensitive probes of N_e than they are of T_e; hence, the [NII] curve indicates N_e > 6.7 × 10⁶ cm⁻³ for T_e < 10000 K and the intersection with the [OIII] and [ArIII] λ5192/3735 curves yields (T_e, N_e) ~ (8400 K, 1.1 × 10⁹ cm⁻³). At such high densities the usual optical diagnostic ratios – [OIII] λ3726/3729, [SII] λλ6716/6731, [ClIII] λλ4571/5538, [ArVIII] λλ4710/4740 – do not return reliable measurements as both their constituent lines are equally affected by collisional
Figure 3. Monochromatic observed flux maps in emission lines arising from LV 2 and vicinity (in units of $10^{-18}$ erg s$^{-1}$ cm$^{-2}$ spaxel$^{-1}$). Recorded with the 6.6 × 4.2-arcsec$^2$ VLT Argus fibre array with 0.31 × 0.31-arcsec$^2$ spaxels (from top to bottom and left to right): C II λ4267, O II λ4649, [O III] λ5007, [Ne III] λ3967, [N II] λ6584, [S II] λ6731, He I λ4471, Hβ λ4861 and the reddening constant from the Hγ/Hβ ratio [the spaxels which show up with large values on row 3 of the ϵ(Hβ) map have been excluded from any analysis]. Spaxels (9–11, 21) correspond to broken fibres. Dark blue masked outer rows/columns are artefacts at the edges of the array introduced during the correction for differential atmospheric refraction (2 spaxels per corner are blank by default as they correspond to sky fibres). North is towards the upper right-hand corner.
de-excitation. Here for the core we adopt representative values of $T_e = 9000 \pm 600$ K and $\log[N_e (\text{cm}^{-3})] = 5.90^{+0.10}_{-0.14}$ for all ions for which abundances are derived in Section 5. The upper density limit is consistent with the C III $\lambda 1907/\lambda 1909$ ratio observations by Henney et al. (2002).

Additional evidence for the existence of high-density ionized gas associated with LV 2 is given by the analysis of several [Fe III] 3d lines detected in the LR3 set-up. The rest-velocity components of these lines are weak in the core spectrum of LV 2 (only the strongest line in the multiplet $\lambda 4658.10$ is detected along with $\lambda 4881$), but their redshifted counterparts arising in gas outflowing from the core are well detected. This indicates that the abundance of iron must be enhanced in the redshifted outflow with respect to the core and to the mean M42 value. An intensity-weighted mean of nine lines yields a heliocentric velocity of $+153 \pm 3$ km s$^{-1}$ for their emitting region. The $\lambda\lambda 4670.7, 4881.1, 4931.0$ and 5011.3 redshifted components show intensity ratios, relative to [Fe III] $\lambda 4658.10$, of 0.103, 0.075, 0.153 and 0.382, respectively; a comparison with the theoretical intensities of Keenan et al. (2001) yields densities of $(1.0-3.8) \times 10^4$ cm$^{-3}$. The above lines return unique solutions to the density. Several more lines are detected ($\lambda\lambda 4701.62, 4733.90, 4769.40, 4777.70$ Å) which provide both low- and high-density solutions. In all these cases, however, the high-density solution is $(2-4) \times 10^5$ cm$^{-3}$ in agreement with the unique values found above. Arguably, if the outflow is this dense then the zero-velocity ionized component at LV 2 could be denser.

Thus both the diagnostic ratio diagrams and the [Fe III] lines indicate that the ionized gas in the core of LV 2 and in the proplyd redshifted outflow is of high density. An independent confirmation of our analysis is provided by Henney et al. (2002) who derived $N_e = 10^6$ cm$^{-3}$ for the bright cusp of the proplyd from the C III $\lambda 1907/\lambda 1909$ HST STIS ratio. (The individual C III doublet components are not resolved in the FOS spectrum of Fig. 2.)

A measurement of the neutral gas density in LV 2 is possible using the [O I] $\lambda 6300/\lambda 5577$ ratio which is sensitive to densities up to $\sim 10^6$ cm$^{-3}$. The $\lambda 6300.34$ line shows several velocity components in the Argus LR5 grating spectrum of the core. A multiple Gaussian fit to the line profile is shown in Fig. 7. Up to five components can be fitted. Two redshifted components are seen, each at a flux level of about 20 per cent with respect to the rest-velocity component (Table 4). The blueshifted components have a total flux of 9 per cent with respect to the rest velocity. In the background spectrum only the $0$ km s$^{-1}$ component is seen, and hence we conclude that the negative and positive velocity counterparts to the line are associated with LV 2 and arise from neutral gas present in the bipolar jet of the proplyd.

The [O I] $\lambda 5577$ line in the LR4 grating shows only the two redshifted components at $V \odot = +62.7 \pm 1.6$ and $+101 \pm 1$ km s$^{-1}$ with a total flux of 20 per cent with respect to the rest component; these are again absent from the background. We thus took two [O I] $\lambda\lambda 6300/\lambda 5577$ ratios using first just the summed flux of the redshifted components and then the rest-velocity components: these are 37.2 and 23.3, respectively (dereddened). At 8400 K they return $N_e$ values of $9.5 \times 10^5$ and $1.8 \times 10^6$ cm$^{-3}$ for the redshifted jet and the core of LV 2, respectively. These results show that there is a reservoir of dense neutral gas in the proplyd which is being photoevaporated from it becoming entrained in a bipolar outflow. This direct measurement of the density in the partly neutral outflow of LV 2 has repercussions for the mass-loss rate from the proplyd.

The fact that very high electron densities are probed via a neutral gas proxy (the [O I] ratio) leads to the conclusion that the emitting OIII volume itself is substantially ionized (while at the same time the density of the inner neutral core of LV 2 must be even larger depending on its temperature). This is supported by the fact that emission from the highly ionized species [S III] is seen at similar velocities. An examination of the [S III] $\lambda 6312.10$ line shows that it has one blueshifted and two redshifted velocity components present only in the LV 2 core spectrum (Fig. 7 and Table 4). Depending on the exact geometry of the outflow this picture would suggest that the gas escaping from LV 2 becomes almost instantly ionized.

5 CHEMICAL ABUNDANCES

In this section elemental abundances in LV 2 are derived using the direct measurements for the $(T_e, N_e)$ obtained above. In Table 5 ionic abundances relative to H I are listed for the core, tail and background regions of LV 2 based on CELs from the Argus data. The core and tail regions correspond to background-subtracted spectra and so these measurement should reflect more accurately the intrinsic composition of the proplyd.

Abundances were also computed from the core, tail and M42 filament FOS observations. For the core, background-subtracted line intensities were used in order to be free from nebular contamination (see last column of Table 2). In this case the tail FOS spectrum was adopted as background due to the 1 arcsec proximity of the respective FOS pointings. The two M42 filament observations were not considered to be suitable for this purpose as they are 55 arcsec away and the Orion nebula surface brightness varies considerably over such scales.

As the precise density stratification of LV 2 is unknown ionic abundances can be sensitive to the choice of $N_e$ for their respective emitting zones if one relies only on lines of low $N_e$; lines of high $N_e$ need to be considered for consistency otherwise some ionic ratios could be underestimated (Rubin 1989). In the determination of

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2 A measurement of the density using [O I] in the background spectrum is not possible as the $\lambda 5577$ line is abnormally strong compared to published values for M42 from Esteban et al. (2004) – this indicates that the line suffers from telluric contamination: the core and tail spectra are immune to this as they are background subtracted.
| Core | Tail | Background |
|------|------|------------|
| c(H\beta) | 1.20 ± 0.08 | 0.98 ± 0.10 | 0.70 ± 0.03 |
| F(H\beta) | (1.570 ± 0.001) \times 10^{-13} | (1.820 ± 0.001) \times 10^{-14} | (7.440 ± 0.001) \times 10^{-14} |
| [O\,\text{III}] λ3726 | 9.46 | 53.0 ± 2.0 | 48.2 ± 0.6 |
| [N\,\text{II}] λ3868 | 45.0 ± 1.2 | 30.7 ± 1.6 | 21.7 ± 0.4 |
| [S\,\text{II}] λ4069 | 2.20 ± 0.10 | 2.90 ± 0.08 | 1.12 ± 0.01 |
| He\,\text{I} λ4471 | 4.22 ± 0.10 | 4.14 ± 0.10 | 5.04 ± 0.10 |
| [Fe\,\text{II}] λ4558 | 0.049 ± 0.008 | 0.233 ± 0.030 | 0.395 ± 0.001 |
| [Ar\,\text{V}] λ4740 | 0.262 ± 0.006 | 0.423 ± 0.036 | 0.273 ± 0.004 |
| [O\,\text{I}] λ4959 | 0.119 ± 0.4 | 111 ± 0.6 | 123 ± 0.1 |
| [Ar\,\text{VII}] λ5192 | 0.151 ± 0.004 | 0.089 ± 0.015 | 0.059 ± 0.024 |
| [Cl\,\text{III}] λ5539 | 0.089 ± 0.005 | 0.399 ± 0.025 | 0.548 ± 0.003 |
| He\,\text{I} λ5876 | 11.8 ± 0.3 | 14.6 ± 0.4 | 17.6 ± 0.1 |
| [O\,\text{I}] λ6300 | 1.54 ± 0.05 | 1.33 ± 0.06 | 0.751 ± 0.010 |
| [S\,\text{II}] λ6312 | 2.18 ± 0.07 | 2.01 ± 0.09 | 2.02 ± 0.02 |
| [N\,\text{II}] λ6584 | 7.94 ± 0.33 | 39.1 ± 2.0 | 32.0 ± 0.5 |
| He\,\text{I} λ6678 | 1.94 ± 0.09 | 2.17 ± 0.12 | 3.53 ± 0.06 |
| [S\,\text{II}] λ6731 | 0.256 ± 0.011 | 2.92 ± 0.16 | 2.89 ± 0.04 |
| Cu\,\text{II} λ4267 | 0.223 ± 0.010 | 0.237 ± 0.036 | 0.218 ± 0.005 |
| O\,\text{II} λ4638 | 0.042 ± 0.007 | – | 0.055 ± 0.003 |
| O\,\text{II} λ4641 | 0.112 ± 0.008 | – | 0.113 ± 0.004 |
| O\,\text{II} λ4649 | 0.154 ± 0.007 | 0.172 ± 0.027 | 0.163 ± 0.004 |
| O\,\text{II} λ4650 | 0.049 ± 0.007 | – | 0.031 ± 0.006 |
| O\,\text{II} λ4661 | 0.043 ± 0.008 | – | 0.052 ± 0.003 |
| O\,\text{II} λ4716 | 0.017 ± 0.006 | – | 0.037 ± 0.004 |

*F(H\beta)* denotes observed fluxes in erg cm\(^{-2}\) s\(^{-1}\) per 0.31 × 0.31 arcsec\(^2\) spaxel; *I(λ)* denotes dereddened relative intensities in units of H\beta = 100. The core and tail values refer to background-subtracted spectra. All entries are for the rest-velocity components of the lines. Entries referring to [O\,\text{III}] λλ3726, 3729 in the core spectrum are uncertain as the peak of LV 2 was very close to the edge of the field of view at this wavelength.

Abundances for O\textsuperscript{2+} and C\textsuperscript{2+} were further computed from their respective O\,\text{II} and C\,\text{II} RLs detected in the three co-added VLT spectra and are included in Table 5. The following expression yields RL abundances relative to H\textsuperscript{+}:

\[
\frac{X^+}{H^+} = \frac{\lambda}{4861.33} \frac{\alpha_{\text{eff}}(H\beta)}{\alpha_{\text{eff}}(\lambda)} \frac{I(\lambda)}{I(H\beta)},
\]

where *I(λ)* is the intensity at wavelength *λ* (Å) of an RL of the recombining ion X\textsuperscript{+1}, and *α_{\text{eff}}(λ)*, *α_{\text{eff}}(H\beta)* are the effective recombination coefficients for the line in question and H\beta, respectively. Recombination coefficients for O\,\text{II} and C\,\text{II} were taken from Storey (1994) and Davey, Storey & Kissielius (2000), respectively.
The He\(^+\)/H\(^+\) ratio was obtained from the He\(\lambda\) 4471, 5876, 6678 RLs (Table 6), using effective recombination coefficients from Smits (1996) and correcting for the effects of collisional excitation using the formulae in Benjamin, Skillman & Smits (1999). A correction for the presence of neutral helium was estimated following Peimbert, Torres-Peimbert & Ruiz (1992) so that

\[
\text{He}/H = \text{He}^+ / H^+ \times \left( 1 + \frac{S^+}{S - S^+} \right).
\]

An estimate of the abundances of elements heavier than He can be made via ionization correction factor (ICF) methods based on standard schemes from the literature. The results are listed in Table 7 for the core, tail, and local background of LV 2 (helium abundances with and without correction for He\(^0\) are included). Corrections for the unobserved ions N\(^2+\), Ne\(^+\), S\(^3+\) and Fe\(^+\) were made as follows:

\[
\text{N}/H = \text{N}^+ / H^+ \times (O^+ + O^2+) / O^+.
\]

\[
\text{Ne}/H = \text{Ne}^{2+} / H^+ \times (O^+ + O^2+) / O^+.
\]



Figure 5. Electron temperature and density solutions for the background-subtracted core of LV 2 (as defined in the text). For [O\(\text{II}\)] and [Ar\(\text{II}\)] dotted lines bracketing thick solid lines correspond to min/max values of the diagnostic ratio. The O\(\pi\) curve is from the [O\(\text{III}\)] \(\lambda\)2470/(\(\lambda\)3726+\(\lambda\)3729) HST ratio.



Figure 6. Electron temperature and density solutions for the (background-subtracted) tail and local background of LV 2. For [N\(\text{II}\)] and [O\(\text{II}\)] dotted lines bracketing thick solid lines correspond to min/max values of the diagnostic ratio.

\[
S/H = (S^+ + S^{2+})/H^+ \times \left[ 1 - \left( \frac{O^+}{O^+ + O^{2+}} \right)^3 \right]^{-1/3},
\]

\[
\text{Fe}/H = 0.9 \times (O^+ / O^{2+})^{0.08} \times (O / O^+ \times \text{Fe}^{2+} / H^+),
\]

following Kingsburgh & Barlow (1994), Peimbert & Costero (1969), Stasińska (1978) and Rodriguez & Rubin (2005), respectively. The abundance of oxygen is the sum of O\(^+/\)H\(^+\) and O\(^2+\)/H\(^+\) ratios, and the abundance of carbon is the sum of C\(^+/\)H\(^+\) and C\(^2+\)/H\(^+\) ratios. For the determination of oxygen and carbon RL abundances we relied on the O\(\text{II}\) and C\(\text{II}\) RLs to obtain O\(^+/\)H\(^+\) and C\(^2+\)/H\(^+\), but added in the O\(^+\)/H\(^+\) and C\(^+/\)H\(^+\) CEL values in each case (in the absence of O\(\text{I}\) and C\(\text{I}\) RLs). No UV carbon lines are detected by FOS from the tail region (the C\(\text{II}\) \(\lambda\)2326 detection is tentative) and so in estimating the carbon abundance using solely the C\(\text{II}\) \(\lambda\)4267 RL we corrected for the presence of C\(^+/\) adopting ICF(C) = O/O\(^+\) (Kingsburgh & Barlow 1994). Finally, in the cases of chlorine and argon we corrected for the presence of Cl\(^+/\) and Ar\(^+/\) adopting ICFs of 1.50 \(\pm\) 0.08 and 1.33 \(\pm\) 0.19, respectively, from the Orion nebula study of Esteban et al. (2004). In Fig. 8 the various abundance measurements for the species considered in this analysis (except helium) are plotted.

5.1 Metallic recombination lines and the abundance anomaly

RLs due to O\(\text{II}\) \(3s–3p\) and C\(\text{II}\) \(4f–3d\) transitions have been recorded by VLT Argus arising from LV 2 providing a measure of the O\(^+/\)H\(^+\) and C\(^2+\)/H\(^+\) abundance ratios independently of the [O\(\text{II}\)] and C\(\text{II}\) CELs. The lines have previously been detected in Herbig–Haro objects in M42 (Blagrave, Martin & Baldwin 2006; Mesa-Delgado et al. 2009), as well as in the diffuse M42 gas (e.g. Esteban et al. 2004). Here, several O\(\text{II}\) V1 multiplet lines near 4650 Å are detected along with C\(\text{II}\) \(\lambda\)4267.15 which is the strongest metallic RL accessible in the optical (Fig. 9). Intensity maps of O\(\text{II}\) \(\lambda\)4649 and C\(\text{II}\) \(\lambda\)4267 are shown in Fig. 3. The lines are intrinsically faint with intensities of less than 1 per cent of H\(\alpha\) but offer the advantage that the ratio of their emissivities to H\(\alpha\) lines is a weak function of the plasma temperature and density (Storey 1994; Storey & Hummer 1995; Liu et al. 1995; Davey et al. 2000; Tsamis et al. 2004).

The derived abundances should thus be less prone to errors resulting from uncertainties in the measurement of these quantities (e.g. Peimbert et al. 1993; Tsamis et al. 2003a; Esteban et al. 2004).
This is in contrast to abundances derived from ratios of CELs to H\textsc{i} lines which have an exponential sensitivity to the electron temperature, and also depend on $N_e$ when CELs of low $N_e$ are used (e.g. Rubin 1989; Tsamis et al. 2003b).

The well-documented abundance anomaly in H\textsc{ii} regions refers to the fact that higher abundances of O\textsuperscript{2+}/H\textsuperscript{+} and C\textsuperscript{2+}/H\textsuperscript{+} are derived from O\textsc{ii} and C\textsc{ii} RLs than from the [O\textsc{iii}] and C\textsc{iii} CELs of the same ions (e.g. Peimbert et al. 1993; Tsamis et al. 2003a; Mesa-Delgado & Esteban 2010). This has repercussions for the representative abundances of O/H and C/H in the nebulae and by extension for the metallicity of the galaxies that host them. The ratio of RL to CEL abundance determinations for a given ion (the so-called abundance discrepancy factor, ADF) takes values from $\sim$2 to 5 in H\textsc{ii} regions, and is best measured for O\textsuperscript{2+} which has RLs (e.g. 4649.13 Å) and CELs (e.g. 4958.91, 5006.84 Å) falling in the blue part of the spectrum that can be observed simultaneously with the same telescope/spectrograph configuration. It is more difficult to obtain the ADF for C\textsuperscript{2+} which has a CEL in the UV (the C\textsc{iii} 1908 Å intercombination doublet) and a RL in the blue (C\textsc{ii} 4267 Å) and be certain that the same volume of nebula is sampled as data obtained from different telescopes/apertures need to be combined.

We take advantage of the cospatial coverage over LV 2 of C\textsc{iii} $\lambda$1908 and C\textsc{ii} $\lambda$4267 with FOS and Argus, respectively, to measure both the C\textsuperscript{2+} and O\textsuperscript{2+} ADFs with a good degree of confidence. In Table 8 the values that we obtained are listed for the LV 2 core, tail and tip positions and for the local nebula background in the form of

$$ADF(X^{2+}) = \frac{\langle X^{2+}/H^+ \rangle_{\text{RL}}}{\langle X^{2+}/H^+ \rangle_{\text{CEL}}}.$$  

(7)

The quoted uncertainties are not due to formal errors but are associated with the variation of the quantity arising from the range of the CEL-computed abundances (with their known sensitivity to $T_e$ and $N_e$). Values are tabulated not only for the background-subtracted spectra but also for the observed spectra which include the M42 nebular emission, so as to examine the difference in the numbers obtained. The O\textsuperscript{2+}/H\textsuperscript{+} and C\textsuperscript{2+}/H\textsuperscript{+} RL ratios in Table 5 were derived from the VLT data. Additionally, the $12 + \log(O^{2+}/H^+)$ and $12 + \log(C^{2+}/H^+)$ RL ratios corresponding to the observed core VLT spectrum are 8.65 ± 0.05 and 8.37 ± 0.04, while those from the observed tail VLT spectrum are 8.57 ± 0.05 and 8.35 ± 0.04,
Table 5. Ionic abundances in LV 2 and its M42 vicinity (in a scale where \( \log H = 12 \)). The employed metallic lines were CELs but RL abundances are also listed for C\(^{2+} \) and O\(^{2+} \).

|        | Core\(^a\) | Tail\(^b\) | Background\(^d\) | Core\(^d\) | Tail\(^e\) | M42\(^f\) |
|--------|------------|------------|------------------|------------|------------|----------|
|        | VLT        | VLT        | VLT              | FOS        | FOS        | FOS      |
| C\(^{+}\) | –           | –          | –                | 8.40 ± 0.17 | 6.35 ± 0.11 | 8.17 ± 0.17 |
| C\(^{2+}\) (RL) | 8.32 ± 0.05 | 8.35 ± 0.05 | 8.32 ± 0.05 | –          | 8.84 ± 0.19 | –         |
| N\(^{+}\) | 7.44 ± 0.14 | 7.17 ± 0.10 | 6.91 ± 0.10 | 7.68 ± 0.14 | 7.29 ± 0.10 | 7.66 ± 0.05 |
| O\(^{+}\) | –          | 8.30 ± 0.23 | 7.90 ± 0.17 | 8.75 ± 0.18 | 7.90 ± 0.09 | 8.53 ± 0.07 |
| O\(^{2+}\) | 8.63 ± 0.14 | 8.13 ± 0.06 | 8.38 ± 0.04 | 8.71 ± 0.15 | 8.32 ± 0.10 | 8.08 ± 0.04 |
| O\(^{3+}\) (RL) | 8.54 ± 0.10 | 8.54 ± 0.10 | 8.57 ± 0.10 | –          | –          | –         |
| Ne\(^{+}\) | 7.94 ± 0.12 | 7.58 ± 0.05 | 7.72 ± 0.05 | 7.96 ± 0.12 | 7.74 ± 0.12 | 7.38 ± 0.06 |
| S\(^{+}\) | 5.73 ± 0.12 | 5.75 ± 0.13 | 5.37 ± 0.12 | –          | 5.51 ± 0.08 | 6.15 ± 0.12 |
| S\(^{2+}\) | 6.77 ± 0.10 | 6.67 ± 0.03 | 7.03 ± 0.05 | 6.63 ± 0.11 | 7.07 ± 0.11 | 6.60 ± 0.05 |
| Cl\(^{2+}\) | 5.18 ± 0.16 | 4.83 ± 0.11 | 5.07 ± 0.05 | –          | –          | –         |
| Ar\(^{2+}\) | 6.44 ± 0.12 | 6.04 ± 0.05 | 6.27 ± 0.05 | 6.53 ± 0.08 | 6.27 ± 0.09 | 6.03 ± 0.11 |
| Ar\(^{3+}\) | 5.30 ± 0.14 | 5.05 ± 0.05 | 5.17 ± 0.05 | –          | –          | –         |
| Fe\(^{2+}\) | 4.67 ± 0.10 | 5.16 ± 0.07 | 5.56 ± 0.05 | –          | –          | –         |

\(^{a}\)The core spectrum is background subtracted. \( T_\text{e} = 9000 ± 600 \text{ K and log}[N_e (\text{cm}^{-3})] = 5.90^{+0.10}_{-0.14} \) was adopted for all ions.

\(^{b}\)The tail spectrum is background subtracted. Adopted \( T_\text{e} = 9700 ± 300 \text{ K and log}[N_e (\text{cm}^{-3})] = 4.58^{+0.24}_{-0.59} \).

\(^{c}\)Adopted \( T_\text{e} = 8400 ± 200 \text{ K for all non-singly ionized species and 9700 ± 500 \text{ K for singly ionized species with } N_e = 4700 ± 1400 \text{ cm}^{-3} \).\)

\(^{d}\)The core spectrum is background subtracted. Adopted \( T_\text{e} = 9050 ± 650 \text{ K with log}[N_e (\text{cm}^{-3})] = 5.92^{+0.08}_{-0.10} \). The entries for the C\(^{2+} \) and O\(^{2+} \) RL abundances correspond to those of core (VLT) as the FOS observation is spatially contained within the core (VLT) observation.

\(^{e}\)Adopted \( T_\text{e} = 8950^{+1550}_{-1250} \text{ K with log}[N_e (\text{cm}^{-3})] = 4.00^{+0.90}_{-0.32} \). The C\(^{+}\) entry is very uncertain as it was obtained from a tentative CN \( \lambda 2326 \) detection.

\(^{f}\)Adopted \( T_\text{e} = 8850 ± 250 \text{ K with log}[N_e (\text{cm}^{-3})] = 4.61^{+0.20}_{-0.38} \).

Table 6. The helium abundance in LV 2 and M42 vicinity.\(^{a}\)

|        | Core | Tail | Background | M42 filament |
|--------|------|------|------------|--------------|
|        | FOS  | VLT  | VLT        | FOS          |
| He\(^{+}\) (\( \lambda 4471 \)) | 0.086 ± 0.018 | 0.078 ± 0.015 | 0.097 ± 0.015 | 0.071 ± 0.016 |
| He\(^{+}\) (\( \lambda 5876 \)) | 0.094 ± 0.009 | 0.095 ± 0.010 | 0.118 ± 0.011 | 0.071 ± 0.011 |
| He\(^{+}\) (\( \lambda 6678 \)) | 0.102 ± 0.038 | 0.053 ± 0.035 | 0.086 ± 0.029 | 0.078 ± 0.042 |
| He\(^{+}\)/H\(^{+}\) avg. | 0.094 ± 0.014 | 0.083 ± 0.010 | 0.108 ± 0.010 | 0.073 ± 0.015 |
| He/H | 0.104 ± 0.018 | 0.088 ± 0.012 | 0.151 ± 0.039 | 0.094 ± 0.026 |

\(^{a}\)The core and tail values are from background-subtracted spectra. Individual values were given weights of 1:3:1 in the computation of the mean according to the relative line intensities. The total He/H ratios incorporate corrections for the presence of neutral helium (equation 2).

respectively. These along with the corresponding CEL values listed in the footnotes of Table 8 were used to obtain the ADFs corresponding to the intrinsic as well as the nebula-contaminated (observed) LV 2 spectra.

6 DISCUSSION AND CONCLUSIONS

The gas-phase abundances of light metals in LV 2 measured via UV and optical emission-line spectroscopy are generally higher than those in the Orion nebula. The differences are the largest for carbon and oxygen when comparing values obtained from CELs. The differences become smaller when the RL results are compared: \( \Delta C = +0.11 \) and \( \Delta O = +0.31 \) dex. Assuming that the RL values for these two elements are more reliable than those of the VLT lines, LV 2 has a carbon abundance a factor of 1.3–1.7 higher than M42 (when comparing with the local background or with Esteban et al. 2004), and a factor of 1.7 higher than the solar value by Asplund et al. (2009). If some of the carbon is locked in grains, particularly in the inner disc regions, then the difference with the Sun would be even higher. For nitrogen there are no substantial differences between LV 2, M42 (for \( r^2 = 0.022 \)) and the Sun. The oxygen abundance in LV 2 is higher by a factor of \( \sim 2 \) compared to the local background, M42, or the Sun. Again the difference with the Sun would be greater if the unknown amount of oxygen incorporated in solids was considered. Neon, which as a noble gas is not expected to be affected by depletion on grains, is also overabundant by a factor of 2.2–2.6 compared to the Sun and the local nebula, or a factor of 1.9 when comparing with the recent determination in M42 of 8.01 ± 0.01, based on Spitzer data (Rubin et al. 2010). The solar Ne abundance is however controversial as Drake & Testa (2005) have advocated a value \( \sim 2.5 \) times higher than that of Asplund et al.; this would bring the LV 2 and solar neon abundances into agreement.

The oxygen and neon abundances in LV 2 are consistent with the range of abundances in the X-ray bright coronae of 35 premain-sequence Orion nebula cluster stars observed by Maggio et al. (2007); the oxygen abundance is \( \sim 0.2 \) dex higher than in 13 early B-type stars of the Ori OB1 association studied by Simón-Díaz (2010).
Table 7. Total gas-phase abundances for the background-subtracted core and tail of LV 2, the local background and a M42 filament (adopting $t^2 = 0$). Independent values for M42 (gas-phase) and the solar photosphere are listed (in units where log H = 12).

| Element | LV 2 core | LV 2 tail | LV 2 background | Filament | M42 ($t^2 = 0$) | M42 ($t^2 = 0.022$) | Sun |
|---------|----------|----------|----------------|----------|----------------|-----------------|-----|
| He      | 10.973   | 10.919   | 11.033         | 10.863   | –              | 10.942          | 10.93 ± 0.01 |
| He      | 11.017   | 10.944   | 11.179         | 10.973   | 10.991         | 10.988          | –              |
| C       | 8.98 ± 0.15 | –        | (8.40 ± 0.13)  | 8.40 ± 0.13 | –              | –              | 8.43 ± 0.05 |
| C (RL)  | 8.66 ± 0.10 | 8.35 ± 0.11; | 8.55 ± 0.08 | –        | 8.42 ± 0.02    | 8.42 ± 0.02    | –              |
| N       | 7.86 ± 0.17 | 7.43 ± 0.12; | 7.46 ± 0.15 | 7.79 ± 0.13 | 7.65 ± 0.09    | 7.73 ± 0.09    | 7.83 ± 0.05 |
| O       | 9.03 ± 0.13 | 8.52 ± 0.15; | 8.51 ± 0.05 | 8.66 ± 0.08 | 8.51 ± 0.03    | 8.67 ± 0.04    | 8.69 ± 0.05 |
| O (RL)  | 8.96 ± 0.10 | 8.74 ± 0.10; | 8.65 ± 0.05 | –        | 8.63 ± 0.03    | 8.65 ± 0.03    | –              |
| Ne      | 8.28 ± 0.06 | 7.93 ± 0.15; | 7.86 ± 0.07 | 7.97 ± 0.10 | 7.78 ± 0.07    | 8.05 ± 0.07    | 7.93 ± 0.10 |
| S       | 6.83 ± 0.25 | 6.74 ± 0.25; | 7.04 ± 0.13 | 6.80 ± 0.15 | 7.06 ± 0.04    | 7.22 ± 0.04    | 7.12 ± 0.03 |
| Cl      | 5.36 ± 0.15 | 5.00 ± 0.05; | 5.25 ± 0.04 | –         | 5.33 ± 0.04    | 5.46 ± 0.04    | 5.50 ± 0.30 |
| Ar      | 6.59 ± 0.05 | 6.21 ± 0.09; | 6.43 ± 0.05 | –         | 6.50 ± 0.05    | 6.62 ± 0.05    | 6.40 ± 0.13 |
| Fe      | 4.96 ± 0.20 | 5.38 ± 0.10; | 6.03 ± 0.05 | –         | 5.86 ± 0.10    | 5.99 ± 0.10    | 7.50 ± 0.04 |

The He entries are before and after including corrections for neutral helium, respectively. The ICF scheme discussed in the text was used. For the core the abundances from FOS were used for carbon and oxygen and the mean of VLT and FOS values were taken for nitrogen and neon; the other values were adopted from the VLT data. For the tail and background the VLT values were adopted; the carbon abundance for the background was adopted from the M42 filament FOS position and may not be strictly representative of the local LV 2 background. References: (1) this paper; (2) Esteban et al. (2004) for two values of the temperature fluctuation parameter, $t^2$ (e.g. Peimbert & Costero 1969) and (3) Asplund et al. (2009).

Figure 8. Ionic gas phase abundances in LV 2 and its Orion nebula vicinity from the present analysis. Abundances were computed from CELs. For C$^2+$ and O$^2+$ abundances from recombination lines are shown as horizontal bars. In the key box 's' refers to values from background-subtracted spectra.

The sulphur abundance is consistent with the M42 value within the uncertainties. Chlorine too is consistent with the M42 value, with the solar C1 abundance. The argon abundance is in agreement with that in B-type stars of the Orion association (6.66 ± 0.06; Lanz et al. 2008), and with the M42 value. The iron abundance is most certainly severely underestimated as the important Fe$^+$ ion is not observed, and a large percentage of the total must be in the dust phase; the same is true for the local nebula as the expected dominant Fe$^{3+}$ ion (e.g. Rubin et al. 1991) is not observed here. As a result, the iron abundance estimates for LV 2 and M42 cannot be directly compared with the Sun.

The second noteworthy result from this study is that the abundance anomaly, classically manifested by ADF(X$^{++}$) > 1.0, goes away when one considers the intrinsic spectrum of the proplyd, that is, with the foreground/background nebula contamination removed (Table 8).$^3$ The upward correction overwhelmingly affects the temperature- and density-dependent CEL diagnostics, not the RLs. In this case the RL and CEL abundances for oxygen come into very good agreement for the core and tip regions of LV 2, which encompass a large part of the luminous flux from the object. The carbon abundance derived from the UV CELs is then a factor of 2–3 higher than the RL value. This however could be due to an underestimation of the $T_e$ in the zone emitting the 1908 Å line, the most temperature-sensitive line in this study; adopting a value in the

$^3$ With the exception of the tail region where the background subtraction was probably not as accurate due to its extended nature.
The protoplanetary disc Laques-Vidal 2 in Orion

in fact lie somewhere between the LV 2 core and local background values.

(ii) The simplest solution to the so-called ADF/O problem encountered in H\(_{\alpha}\) regions would then be one where density inhomogeneities are playing havoc with the classic forbidden-line diagnostics.

(iii) The metallicity of nebulae where spatially resolved observations are impossible, such as extragalactic H\(_{\alpha}\) regions, will need to be corrected upwards. Whether there will be repercussions for cosmic chemical evolution studies will depend on the correction factor and how that factor varies with metallicity or other properties of the ionized interstellar medium, such as the degree of 'clumpiness'.

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Figure 9. The C\(_{\text{II}}\) 4267.15 Å 3d\(^2\)D–4f\(^2\)F\(^o\) and O\(_{\text{III}}\) V1 multiplet 3s\(^2\)P–3p\(^2\)D\(^0\) recombination lines on the VLT Argus spectrum of LV 2 at a resolution of 9.5 km s\(^{-1}\) pixel\(^{-1}\). Black: observed (proplyd + M42 nebula), blue: local M42 nebula background and red: LV 2 core (observed minus the background). Note the blueshifted and redshifted components of [Fe in] 4658 Å which arise in the outflow.

| Table 8. Abundance discrepancy factors: the ratio of RL to CEL abundance determinations for O\(^{2+}\) and C\(^{2+}\), \(^a\) |
|---------------------------------|------------------|
|                                  | ADF(O\(^{2+}\))  | ADF(C\(^{2+}\))  |
| Core (VLT)                       | 0.4\(^{+}0.8\)   | 0.8\(^{+}1.0\)   |
| Core (FOS)                       | 0.7\(^{+}0.9\)   | 1.0\(^{+}1.2\)   |
| Tail (VLT)                       | 3.3\(^{+}0.7\)   | 3.6\(^{+}0.8\)   |
| Tip (FOS)                        | 3.3\(^{+}0.7\)   | 3.6\(^{+}0.8\)   |
| Background (VLT)                 | 1.4\(^{+}0.6\)   | 1.0\(^{+}0.4\)   |

\(^a\) The C\(^{2+}/H\(^{+}\) and O\(^{2+}/H\(^{+}\) RL ratios were obtained from the VLT spectra in all cases (Table 3). In units where log H = 12 the corresponding CEL abundance ratios used to compute the ADFs are: for the background-subtracted spectra of core (VLT), core (FOS), tail (VLT) see Table 5; for tip (FOS): O\(^{2+}\) = 8.75, C\(^{2+}\) = 8.85 (at T\(_e\) = 9000 K, log[N\(_e\) (cm\(^{-3}\)] = 5.81). For the observed spectra – core (VLT): O\(^{2+}\) = 8.38\(^{+}0.23\) (at T\(_e\) = 9650 ± 1350 K, log[N\(_e\) (cm\(^{-3}\)] = 5.29\(^{+}0.29\) see Table 3); core (FOS): O\(^{2+}\) = 8.33\(^{+}0.19\) and C\(^{2+}\) = 8.29\(^{+}0.24\) using data from Table 2; for tail (FOS) see Table 5; tip (FOS): O\(^{2+}\) = 8.13\(^{+}0.08\) and C\(^{2+}\) = 7.79\(^{+}0.13\) using data from Table 2; for background (VLT) see Table 5.

The C\(^{2+}/H\(^{+}\) and O\(^{2+}/H\(^{+}\) RL ratios were obtained from the VLT spectra in all cases (Table 3). In units where log H = 12 the corresponding CEL abundance ratios used to compute the ADFs are: for the background-subtracted spectra of core (VLT), core (FOS), tail (VLT) see Table 5; for tip (FOS): O\(^{2+}\) = 8.75, C\(^{2+}\) = 8.85 (at T\(_e\) = 9000 K, log[N\(_e\) (cm\(^{-3}\)] = 5.81). For the observed spectra – core (VLT): O\(^{2+}\) = 8.38\(^{+}0.23\) (at T\(_e\) = 9650 ± 1350 K, log[N\(_e\) (cm\(^{-3}\)] = 5.29\(^{+}0.29\) see Table 3); core (FOS): O\(^{2+}\) = 8.33\(^{+}0.19\) and C\(^{2+}\) = 8.29\(^{+}0.24\) using data from Table 2; for tail (FOS) see Table 5; tip (FOS): O\(^{2+}\) = 8.13\(^{+}0.08\) and C\(^{2+}\) = 7.79\(^{+}0.13\) using data from Table 2; for background (VLT) see Table 5.
