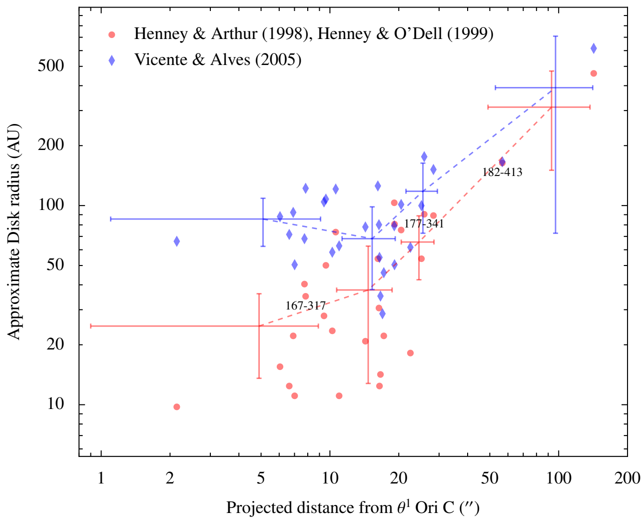

Figure 12. Variation with projected distance from the ionizing star of circumstellar disc sizes in the Orion proplyds. Blue symbols show empirical determinations from Vicente & Alves (2005), red symbols show results from fitting photoevaporation models (Henney & Arthur 1998; Henney & O'Dell 1999). The three proplyds that have been subject to gas-phase abundance studies are marked: 167-317 (LV 2), 177-341 (HST 1), a 182-413 (HST 10). In only a few cases, such as HST 10, is the molecular disc size directly measured, for the rest it is assumed to be half the size of the ionization front. Note that the Vicente & Alves methodology significantly overestimates the true size of the ionization front (and by extension the enclosed disc) for proplyds that are much brighter than surrounding nebula, which tend to be those found close to the ionizing star. Error bars show the mean and standard deviation measured in 4 broad spatial bins.

4.3 Comparison with other proplyds

HST 10 is the third proplyd to be subject to a detailed abundance analysis, following earlier studies of LV 2 (Tsamis et al. 2011; Tsamis & Walsh 2011) and HST 1 (Mesa-Delgado et al. 2012). These proplyds cover a broad range in size and in separation from the Trapezium stars (see Figure 12), and derived physical parameters for the three proplyds are summarised in Table **??**. HST 10 shows a significantly lower ionization parameter than the two closer-in proplyds, which is reflected in its emission line spectrum that is relatively stronger in low ionization lines. Despite these differences, the estimated mass loss rate from the ionized cusp is very similar for all three proplyds, being of order $2 \times 10^{-7}\ M_{\odot}\ \mathrm{yr}^{-1}$. These values are somewhat lower than earlier estimates (e.g., Henney & O'Dell 1999; Henney et al. 2002), which is partly because we are neglecting the contribution of mass loss though the proplyd tail.

Table 5 also shows estimates for the mass and radius of the embedded circumstellar accretion disk, which is the reservoir of mass in the proplyds. All three proplyds show very similar sub-mm fluxes (Mann & Williams 2010), of order 20 mJy once the contribution from ionized free-free emission has been subtracted. However, conversion of this flux to a gas mass requires knowledge of the dust opacity per unit gas mass and dust temperature, both of which have large uncertainties (Williams & Cieza 2011). The values in the table are calculated on the assumption that the dust temperature is the effective temperature of a disk in radiative equilibrium with the bolometric flux from the Trapezium stars,* and using the opacity recommended by (Beckwith et al. 1990) of $0.1(\nu/1000\ \mathrm{GHz})\ \mathrm{cm^2\ g^{-1}}$, giving $0.034\ \mathrm{cm^2\ g^{-1}}$ at 880 μm. It must be emphasised that the derived masses are highly uncertain, since the opacity could be up to 20 times smaller if substantial grain growth up to cm-sized bodies has occured (D'Alessio et al. 2001). Evidence for grain evolution has been found in the case of silhouette disks projected onto the Orion Nebula (Miotello et al. 2012). The masses given in the table are at least 6 times smaller than the "minimum mass solar nebula" (Weidenschilling 1977), which is the mass within 30 AU required to account for the composition of the planets in the Solar System.

The nominal photoevaporation timescales, $t_{\mathrm{evap}} = M_{\mathrm{d}}/\dot{M}$, are uncomfortably short compared with the estimated age of the photoionized nebula ($\geqslant 10^5$ yr; see discussion in § 8.2.2 of Henney & O'Dell 1999), but would come into agreement if the masses were increased by a factor of 5–10, which cannot be ruled out (see previous paragraph). Interestingly, the evaporation timescale t_{evap} *increases* with increasing distance from the Trapezium. Given that t_{evap} should be roughly equal to the elapsed time since the disk photoevaporation commenced (Johnstone et al. 1998), this is the opposite of what would be expected from a naive model of a roughly spherical H II region, in which case proplyds at greater distances from the ionizing star would have entered the H II region more recently. However, evidence from both observations (O'Dell et al. 2009) and numerical simulations (Arthur et al. 2011) point to the continued survival of dense clumps of molecular gas well inside the apparent boundary of the H II region, in which case it is reasonable that the proplyds closest to the Trapezium might have been shielded from ultraviolet radiation until relatively recently.

The abundance results for the three proplyds are rather disparate, so that it is very hard to see any consistent trend in the results. For instance, although we find a roughly solar oxygen abundance for HST 10 from both empirical analysis and photoevaporation model fitting, the oxygen abundance was found to be $\simeq 3\times$ super-solar in LV 2 (Tsamis et al. 2011) from a purely empirical analysis, with no discrepancy between collisional and recombination lines. In contrast, Mesa-Delgado et al. (2012) found oxygen to be $\simeq 3\times$ *sub*-solar in HST 1, both from empirical analysis of CELs and from photoevaporation model fitting, whereas an empirical analysis of ORLs is more consistent with a solar value. Given the wide range of characteristic ionization and density found in the three proplyds (Table 5), it is possible that systematic errors in our abundance analysis might be contributing to this wide spread. In order to rule out any such effects, it is vital to carry out a similar analysis on a sample of proplyds that all have *similar* ionization parameters and densities.

REFERENCES

Arthur S. J., Henney W. J., Mellema G., de Colle F., Vázquez-Semadeni E., 2011, MNRAS, 414, 1747
Beckwith S. V. W., Sargent A. I., Chini R. S., Guesten R., 1990, AJ, 99, 924
D'Alessio P., Calvet N., Hartmann L., 2001, ApJ, 553, 321
Henney W. J., Arthur S. J., 1998, AJ, 116, 322
Henney W. J., O'Dell C. R., 1999, AJ, 118, 2350
Henney W. J., O'Dell C. R., Meaburn J., Garrington S. T., López J. A., 2002, ApJ, 566, 315

* Although the sub-mm emission is optically thin, the disks are likely to be optically thick at mid-infrared wavelengths where they emit the bulk of their radiation. We assume that 50% of the bolometric radiation from the Trapezium stars is absorbed in the ionized cusp of the proplyd, and that 50% of the remainder is absorbed in the neutral photoevaporation flow, so that only 25% reaches the surface of the disk.

Table 5. Comparison of physical properties between HST 10 and two other well-studied proplyds

	Units	Note	LV 2	HST 1	HST 10
Coordinate-based designation		1	167-317	177-341	182-413
Relation to ionizing source					
Projected distance, D'	$''$	2	7.83	25.84	56.7
Inclination, i	$^\circ$	3	50	70	150
True distance, D	pc	4	0.022	0.059	0.242
Ionized cusp					
Ionization front radius, r_0	AU	5	53.	136.	247.
Peak electron density, n_0	10^6 cm^{-3}	6	2.0	0.4	0.1
Ionization parameter		7	0.012	0.008	0.002
Cusp mass-loss rate, $\dot{M}$	10^{-7} $M_\odot$ yr^{-1}	8	2.6	2.5	2.1
Molecular disc					
Disc effective temperature: T_d	K	9	95	58	29
Disc mass M_d	10^{-3} $M_\odot$	10	1.6	2.7	5.4
Disc radius R_d	AU	11	34	89	160
Evaporation time, t_{evap}	10^4 yr	12	0.6	1.1	2.6

Notes: (1) O'Dell & Wen (1994) (2) Angular separation from θ^1 Ori C (O'Dell 1998) (3) Inclination of proplyd axis to line of sight estimated from kinematic studies of the velocity–ionization correlation in emission lines from the cusp (Henney & O'Dell 1999; Henney et al. 2002). Proplyds with $i > 90^\circ$ have their head pointing away from the observer. (4) $D = D' / \sin i$. (5) Estimated from fitting evaporation models to the Hα profiles of the cusps Henney & Arthur (1998). (6) LV 2 from [C III] density (Henney et al. 2002); HST 1 and HST 10 from model fitting (this paper and Mesa-Delgado et al. 2012). (7) $F/(n_0\, c)$. (8) Calculated by integrating model mass fluxes over the area of the cusp. (9) Radiative equilibrium temperature, assuming that 25% of the bolometric flux from θ^1 Ori C reaches the surface of the disk (see also Robberto et al. 2002). (10) Estimated from observed fluxes at 880 μm (Mann & Williams 2010) after subtracting the contribution from ionized free-free emission, assuming optically thin dust emission with opacity $\kappa_\nu = 0.034$ cm^2 g^{-1} and dust temperature equal to the effective temperatures derived above. (11) Directly estimated from *HST* images from HST 10. For LV 2 and HST 1, we assume $r_d = 0.65 r_0$, see Figure 12. (12) Nominal mass loss timescale: $M_d / \dot{M}$.

Johnstone D., Hollenbach D., Bally J., 1998, ApJ, 499, 758

Mann R. K., Williams J. P., 2010, ApJ, 725, 430

Mesa-Delgado A., Núñez-Díaz M., Esteban C., García-Rojas J., Flores-Fajardo N., López-Martín L., Tsamis Y. G., Henney W. J., 2012, MNRAS, 426, 614

Miotello A., Robberto M., Potenza M. A. C., Ricci L., 2012, ApJ, 757, 78

O'Dell C. R., 1998, AJ, 115, 263

O'Dell C. R., Henney W. J., Abel N. P., Ferland G. J., Arthur S. J., 2009, AJ, 137, 367

O'Dell C. R., Wen Z., 1994, ApJ, 436, 194

Robberto M., Beckwith S. V. W., Panagia N., 2002, ApJ, 578, 897

Tsamis Y. G., Walsh J. R., 2011, MNRAS, 417, 2072

Tsamis Y. G., Walsh J. R., Vílchez J. M., Péquignot D., 2011, MNRAS, 412, 1367

Vicente S. M., Alves J., 2005, A&A, 441, 195

Weidenschilling S. J., 1977, Ap&SS, 51, 153

Williams J. P., Cieza L. A., 2011, ARA&A, 49, 67