Two jets from the Orion (M42) ‘proplyds’ – kinematics, morphologies and origins.

J. Meaburn¹, M. F. Graham¹ & M. P. Redman².

¹Jodrell Bank Observatory, Dept of Physics & Astronomy, University of Manchester, Macclesfield, Cheshire SK11 9DL, UK.
²Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BE, UK.

Received **insert**; in original form **insert**

ABSTRACT
A spatially unresolved velocity feature, with an approaching radial velocity of ≈ 100 km s⁻¹ with respect to the systemic radial velocity, in a position–velocity array of [O iii] 5007 Å line profiles is identified as the kinematical counterpart of a jet from the proplyd LV 5 (158–323) in the core of the Orion Nebula. The only candidate in HST imagery for this jet appears to be a displaced, ionized knot. Also an elongated jet projects from the proplyd GMR 15 (161–307). Its receding radial velocity difference appears at ≈ 80 km s⁻¹ in the same position–velocity array.

A ‘standard’ model for jets from young, low mass stars invokes an accelerating, continuous flow outwards with an opening angle of a few degrees. Here an alternative explanation is suggested which may apply to some, if not all, of the proplyd jets. In this, a ‘bullet’ of dense material is ejected which ploughs through dense circumstellar ambient gas. The decelerating tail of material ablated from the bullet’s surface would be indistinguishable from a continuously emitted jet in current observations.

Key words: stars: Orion – line: profiles – stars: winds, outflows – ISM: jets and outflows

1 INTRODUCTION

The nature of the compact gaseous knots, dubbed ‘proplyds’ by O’Dell, Wen & Hu (1993), in the close vicinity of the O6 star θ¹ Ori C in the Orion Nebula, is becoming increasingly clear. They were first identified (LV 1-6) by Laques & Vidal (1979) in the optical emission lines with many more identified later as sub-arcsec diameter thermal radio sources (Churchwell et al. 1987; Garay 1987; Garay, Moran & Reid 1987 - hereafter GMR; Felli et al. 1993a; Felli et al. 1993b). Each proplyd was shown to contain a low mass star (Meaburn 1988; McCaughrean & Stauffer 1994) whose youth is suggested by this partial cocoon of primaeval material (see the dramatic HST images in O’Dell, Wen & Hu 1993; O’Dell & Wong 1996; Bally et al. 1998). The ≈ 50 km s⁻¹ photoevaporated flows, driven by the intense Lyman flux of θ¹ Ori C, from the ionized proplyd surfaces (Meaburn 1988) and their interactions with the particle wind from θ¹ Ori C to form stand-off bow-shocks (Hayward, Houck & Miles 1994) have most recently been considered by Henney et al. (2002) and Graham et al. (2002) and references therein.

Jets from young stellar objects (YSOs) were considered as one plausible explanation of the ≥ 100 km s⁻¹, highly collimated (≤ 1″ wide) velocity ‘spikes’ on longslit position-velocity (pv) arrays of [O iii] 5007 Å line profiles in ground-based observations of proplyds (Meaburn et al. 1993; Massey & Meaburn 1995). The ubiquity of such jets from the proplyds then became immediately apparent in the HST imagery of Bally, O’Dell & McCaughrean (2000). The HST spectral observations, with STIS at 0.1” resolution of the C iii] 1907 & 1909 Å profiles from the jet of LV 2, showed the jet outflow to have a radial velocity extent of ≈ 120 km s⁻¹ (Henney et al. 2002). This is consistent with the extent of the velocity spike in the ground-based 1” resolution observations of the [O iii] 5007 Å profiles from LV 2 (fig. 5 in Meaburn et al. 1993; Henney et al. 2002). Consequently, it is safe to assume that the narrow velocity spikes in all of the pv arrays of [O iii] 5007 Å profiles observed from the ground in other proplyds are a measure of their jet velocities.

In the present paper this assumption has been applied to two proplyds, LV 5 (158–323) and possibly GMR 15 (161–307), where high-speed, collimated, velocity features (‘spikes’) have been found in the pv arrays of [O iii] 5007 Å profiles observed from the ground and where convincing HST images of their jets exist. The bracketed identifications are from O’Dell & Wen (1994).

2 OBSERVATIONS AND RESULTS

The proplyds LV 5 and GMR 15 are sketched against various features of the Trapezium cluster in the core of the
Orion nebula in Fig. 1. The [O iii] 5007 Å line profiles were obtained with the Manchester echelle spectrometer (MES - Meaburn et al. 1984) combined with the Isaac Newton Telescope (INT) at various times between 1991 and 1993. Full details of the observational setup are reported in Massey & Meaburn (1995). The most notable aspect of the observation along slit length marked Pos. 1 in Fig. 1 was that sub-arcsec 'seeing' prevailed. A resolution of 0.9″ was achieved in practice.

The pv array of [O iii] 5007 Å line profiles is compared in Fig. 2 with a section of the HST [O iii] 5007 Å archive image (from the GO 5469 programme of J. Bally). The MES slit orientation and width is indicated. For LV 5 an attempt has been made to isolate the [O iii] 5007 Å emission line profile from the proplyd from the strong emission line profile of the nebular background. This was achieved by extracting the [O iii] 5007 Å profile which included the proplyd from an 0.9″ length of the pv array. The mean of two profiles from adjacent and equal lengths of the slit, above and below this position, after interpolation, was then subtracted. The results of this procedure for LV 5 are shown in Fig. 3. The only uncertain parts of this profile are from the conservatively large heliocentric radial velocity range $V_{\text{hel}} = 15$ to 35 km s$^{-1}$ which contains the intense [O iii] 5007 Å emission around the systemic heliocentric radial velocity ($V_{\text{sys}} \approx 25$ km s$^{-1}$) of M42.

The HST [O iii] 5007 Å archive images of LV 5 and GMR 15, along with its jet, j160-307 (Bally et al. 2000) are shown in Figs. 4 and 5 respectively for comparison. Here the jet candidates are identified. The velocity component marked 'bow-shock' in Fig. 3 is coincident with the similarly spatially extended feature in the pv array in Fig. 2 that must originate in the arc of emission (see Fig. 4) towards $\theta^1$Ori C. It is reasonable to assume that this arc delineates the bow-shock as the particle wind of $\theta^1$Ori C encounters the obstruction of LV 5 and its photo-evaporating gas.

The high-speed ‘spike’ from $V_{\text{hel}} = -40$ to -80 km s$^{-1}$ in the pv array in Fig. 2 (and see its identification in the profile in Fig. 3) is convincingly that expected of a jet from LV 5 whose width is unresolved by the 0.9″ resolution of these ground-based observations. The knot adjacent to LV 5, identified in the HST image in Fig. 4, is the only available candidate for such a jet. Several of the jets identified by Bally et al. (2000) had the appearance of similar faint emission line knots.

The positive velocity ‘spike’ in Fig. 2, closely associated with the proplyd LV 6, is similarly narrow and extends to $V_{\text{hel}} \approx 100$ km s$^{-1}$. However, there is no corresponding jet-like feature in the HST image. The broader ‘spike’ in Fig. 2 where the slit passes between knot 14 and 24 is less convincingly of proplyd origin even though it extends to $V_{\text{hel}} \approx 120$ km s$^{-1}$. Here the slit intersects a filament which may have a Herbig-Haro like nature (Canto et al. 1980).

However, a trace of the velocity ‘spike’ of the very pos-
Figure 2. The HST [O iii] 5007 Å image (left hand panel) of the region surrounding Pos. 1 in Fig. 1 aligned with the [O iii] 5007 Å pv array of this slit position. The image is centered on Pos. 1 and the white lines indicate a width of 1″, which corresponds to the slit width of 0.4″ convolved with seeing of 0.9″. The vertical extent of the pv array (along the slit) is 41″.

Figure 3. An [O iii] 5007 Å profile taken with the MES of the proplyd LV 5. The nebula background has been subtracted by interpolating adjacent regions either side of LV 5 along the slit length.
Figure 4. HST [O III] 5007 Å image of LV 5 and LV 6. LV 5’s possible jet is indicated along with the bow-shock due to the interaction of the proplyd flow and the wind of $\theta^1$Ori C.

Figure 4

In an attempt to understand the nature of the proplyd jets, one can compare them to the molecular jets seen in low mass star forming regions. Some of these molecular outflows have also been observed to be characterised by a ‘Hubble-like’ velocity law (see e.g. Lada & Fich 1996) such that the highest velocity gas is found furthest from the star implying an acceleration outwards along the length of the jet.

3 DISCUSSION

In an attempt to understand the nature of the proplyd jets, one can compare them to the molecular jets seen in low mass star forming regions. Some of these molecular outflows have also been observed to be characterised by a ‘Hubble-like’ velocity law (see e.g. Lada & Fich 1996) such that the highest velocity gas is found furthest from the star implying an acceleration outwards along the length of the jet.
This has the implication that all of the gas has the same dynamical timescale. Acceleration mechanisms for such outflows are unclear at present but the most popular possibility is that the molecules are accelerated in jet-driven bowshocks (Downes & Ray 1999) though there are problems with most of the current models (Lada & Fich 1996). A straightforward view would then be that the proplyd jets are simply continuous, nearly collimated, outflows from the YSO to the jet tips with jet opening angles of \( \lesssim 10^\circ \) if they are unresolved by the HST 0.1" resolution and if they have a length of 0.5". See Meaburn & Dyson (1987) for such a model applied to HH 46-47 and its first application to proplyd jets by Bally et al (2000). Such models would of course have to be modified, mainly to account for the highly ionizing environment, but also because the mass and momentum flux of these jets are rather feeble compared with that from HH 46-47 (Henney et al 2002). The jet material will be ionized unless it is shielded from \( \theta^1 \) Ori C by the proplyd disk and Raga et al (2000) have shown that in fact all the jet material will be promptly ionized in this way so that a neutral core within the jet is unlikely. The image of such a jet from an Orion proplyd would be indistinguishable from that from GMR 15 in Fig. 5 because its declining width towards the proplyd YSO would be unresolved by HST.

As ballistic high-speed 'bullets' are associated with several circumstellar eruptive phenomena [see Lopez, Meaburn & Palmer (1997), Bryce et al (1997) and O'Connor et al (2000) for PNe and Redman, Meaburn & Holloway (2002) for the Luminous Blue Variable, Eta Carinae] an alternative explanation of the proplyd jets is worth considering. They could be a consequence of bullets with ablated flows. Incidentally, although such bullet phenomena are observationally well established in a variety of circumstellar environments their origins are far from being understood.

### 3.1 The bullet/ablated trail model

The jet candidate appears as a single knot adjacent to LV 5 in Fig. 4 (and in other examples in Massey & Meaburn 1995 and Bally et al. 2000) an explanation as a collimated outflow is not too convincing (unless only the bow-shocked gas at the tip of a collimated monopolar jet is being seen). However, a simple variant on the model involving a collimated, continuous outflow is suggested that may be applicable in some proplyd jet systems. Instead of the jet being generated by continuous mass loss from the central system, a single brief mass ejection event from the YSO is postulated. This will give rise to a dense clump of ejecta material which will behave like a ballistic bullet since it will not be continually accelerated. In this model for a proplyd jet it is assumed that photo-ionized material is ablated (Dyson, Hartquist & Biro 1993; Klein, McKee & Colella 1994) off the bullet head as it
ploughs through ambient gas leaving a trail in its wake. The trail will broaden at approximately the sound speed and be decelerated by oblique shocks. This could appear in the HST images as a compact knot of photoionised emission possibly decelerating towards the YSO but again resembling, at 0.1" resolution, the jet protruding from GMR 15 in Fig. 5. Within this explanation the distinction between the GMR 15 elongated jet and LV 5 compact knot could simply be that the bullet causing the extended GMR 15 feature is ploughing through denser circumstellar gas causing more ablation. The decelerating ‘strings’ of high-speed gas, preceded by bullets from the explosive LBV star, η Carinae seem to be particularly well described by such a model (Redman, Meaburn & Holloway, 2002) and motivates this suggestion although the ejection speeds involved in the proplyd phenomenon are $\approx 10$ times lower.

The apparent length of the proplyd jets are $\approx 0.5$ arcsec, giving them a physical length of $\approx 200$ au or $3 \times 10^{10}$ cm. If the bullet is travelling at $\approx 120$ km s$^{-1}$ and has not slowed down significantly then it was ejected from the proplyd approximately 10 years ago. Repeated HST observations should clearly detect the motion of these features on a timescale of just a few years. The jet width is not resolved by the HST at distance of the Orion nebula, 450pc, which implies that the diameter of the jet is $< 45$ au or $7 \times 10^{14}$ cm. If the jet represents a decelerating wake behind a bullet then it is unlikely that the bullet is significantly wider than the wake.

Within this bullet/ablated flow model, the maximum length of the trail is controlled by how far the bullet is able to travel into the ambient medium before being destroyed. The destruction length depends on the density contrast between the clump and ambient medium $\xi = n_c/n_i$. The emission measure of jet j160-307 (measured by Bally et al 2000) leads to a density estimate of $n_c = 1.3 \times 10^5$ cm$^{-3}$ for the jet material. This corresponds to a density contrast of $\xi \approx 50$ between this material and the background density in Orion. Thus the original bullet should have been denser by a factor of at least this much. Henney et al (2002) using the models of Raga et al (2000) point out that any condensation dense enough to remain neutral while being exposed to the ionizing radiation from θ Ori C will have a surface brightness comparable to the proplyd surface since in both cases the emission will be from gas that has just passed through a D-type ionization front. This does not rule our model out because the density required for the ionization front to be D-type is $2 \times 10^8$ cm$^{-3}$ or $\xi \sim 10^7$. This is far greater than that expected from the bullet in our model and thus the bullet is likely to be ionized throughout. Furthermore, the ionization front will have been the fast R-type with a propagation velocity of $\sim 10^4$ km s$^{-1}$ so that the bullet would have been ionized very soon after being ejected from the proplyd.

There are two clear characteristics that should distinguish a bullet and ablated trail from its continuous outflow competitor. Firstly the former will broaden towards the YSO and the latter become narrow. Secondly, the ablated trail would exhibit deceleration along its length towards the YSO and, if spatially resolved in this direction, show as a linear change in radial velocity towards the YSO. This characteristic would appear, if the trail/jet is unresolved as in the present ground based spectral observations in Fig. 2, as a broad velocity spike down to $V_{\text{sys}}$ in a pv array of line profiles. The continuous non-accelerating jet, in contrast, would have a reasonably uniform speed along its length and appear as a narrow, isolated, high-speed feature, displaced from $V_{\text{sys}}$, in such pv arrays. STIS observations down the length of the jet could discriminate between these possibilities.

4 CONCLUSIONS

An elongated jet in an HST image projecting from proplyd GMR 15 appears as a velocity ‘spike’ in the corresponding pv array obtained with MES. Also, the only jet candidate to explain the high-speed unresolved feature in an MES pv array is found to be a displaced ionized knot in the HST imagery of the proplyd LV 5.

Two distinctly different dynamical explanations are considered for these jets. In many cases standard jet models (suitably modified for the conditions within the Orion Nebula) may be able to describe proplyd jets. However, we suggest that in some instances it may be more useful to model them as being due to the passage of discrete bullets of ejecta that are promptly ionized and that are ablated as they travel through the ambient medium. The trailing ablated material is then identified as the jet, with the bullet at its head. Such a dynamical mechanism has the attraction that the ‘Hubble-type’ velocity law, if found in future observations of the proplyd jets, is naturally explained since material that was ablated earlier has slowed down more than material more recently incorporated into the flow. Kinematic differences between this model and a continuous jet model could be investigated using STIS spectroscopy with its 0.1" resolution.

ACKNOWLEDGEMENTS

MPR and MFG are supported by a PPARC Research Assistantship and a Research Studentship respectively.

REFERENCES

Bally J., Sutherland R. S., Devine D., & Johnstone D. 1998, AJ, 116, 293.
Bally J., O’Dell C. R., & McCaughrean M. J. 2000, AJ, 119, 2019.
Bryce, M., López, J. A., Holloway, A. J. & Meaburn, J. 1997, ApJ, 487, L161.
Cantó J., Goudis C., Johnson P. G., & Meaburn J. 1980, A&A, 85, 128.
Churchwell E., Felli M., Wood D. O. S., & Massi M. 1987, ApJ, 321, 516.
Downes T.P., Ray T.P., 1999, A&A, 345, 977.
Dyson J. E., Hartquist T. W., & Biro S. 1993, MNRAS, 261, 430.
Felli M., Churchwell E., Wilson T. L., & Taylor G. B. 1993, A&ASS, 98, 137.
Felli M., Taylor G. B., Catarzi M., Churchwell E., & Kurtz S. 1993, A&ASS, 101, 127.

Garay G. 1987, Revista Mexicana de Astronomia y Astrofisica, vol. 14, 14, 489.

Garay G., Moran J. M., & Reid M. J. 1987, ApJ, 314, 535 (GMR)

Graham M. F., Meaburn J., Garrington S. T., O’Brien T. J., Henney W. J., & O’Dell C. R. 2002, ApJ, 570, in press.

Klein R. I., McKee C. F. & Colella P. 1994, ApJ, 420, 213.

Hayward T. L., Houck J. R., & Miles J. W. 1994, ApJ, 433, 157

Henney W. J., O’Dell C. R., Meaburn J., Garrington S. T., & Lopez J. A. 2002, ApJ, 566, 315

Lada C.J., Fich M., 1996, ApJ, 459, 638

Laques P., & Vidal J. P. 1979, A&A, 73, 97

López J. A., Meaburn, J. & Palmer, J. W. 1997, ApJ, 415, L135.

Massey R. M., & Meaburn J. 1995, MNRAS, 273, 615

McCaughrean M. J., & Stauffer J. R. 1994, AJ, 108, 1382.

Meaburn J., Blundell B., Carling R., Gregory D. F., Keir D., & Wynne C. G. 1984, MNRAS, 210, 463.

Meaburn J. & Dyson J. E. 1987, MNRAS, 225, 863.

Meaburn J. 1988, MNRAS, 233, 791.

Meaburn J., Massey R. M., Raga A. C., & Clayton C.A. 1993, MNRAS, 260, 625.

O’Connor J. A., Redman M. P., Holloway A. J., Bryce M., Lópex J. A. & Meaburn J. 2000, ApJ, 531, 336.

O’Dell C. R., Wen Z., & Hu X. 1993, ApJ, 410, 696.

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

O’Dell C. R., & Wong K. 1996, AJ, 111, 846.

Raga A.C., Lopez-Martín L., Binette L., López J.A., Cantó J., Arthur S.J., Mellema G., Steffen W., Ferruit P., 2000, MNRAS, 314, 681.

Redman M. P., Meaburn J., & Holloway A. J. 2002, MNRAS, 332, 754.