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AN ATLAS OF STATIONARY BOW SHOCK ARCS IN THE ORION NEBULA

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Abstract

We present a complete catalog of all the stationary emission line arcs (LL objects and proplyd bowshocks) found in archival HST imaging of the Orion Nebula. The total number of objects detected is 73, of which 20 have not previously been reported in the literature. We classify the shapes of emission line arcs by fitting conic sections to the inner and outer shell boundaries and calculate the background corrected H alpha surface brightness of each object. We find significant differences in the shell shapes between the objects closest to the ionizing stars and those farther away. The closer group, which all represent proplyd interactions with the hypersonic stellar wind, have relatively closed shapes, while the farther group, which are due to interactions with the transonic ionized champagne flow in the nebula, are more open and hyperbolic. Although some of the latter group are also known proplyds, many are not, and the largest and brightest arcs tend to be associated with particularly luminous young stars, suggesting that the intrinsic T Tauri disk wind may play a role. The orientations of the arcs, together with the stagnation pressures estimated from the surface brightness, allow the internal velocity field of the H II region to be probed. We find that approximately radial flows from the core of the nebula dominate over disordered, turbulent flows.

1. INTRODUCTION

2. OBSERVATIONS

We have attempted to identify and characterize all stationary emission-line arcs in archival HST imaging observations of the Orion Nebula, obtained with the WFPC2 and ACS cameras, as summarized in Table 1. The primary dataset that we have used is the 26-orbit Cycle 12 program GO 9825 (Bally et al. 2006). This program covered a significant fraction of the entire nebula with the ACS/WFC camera in the filter F658N, which transmits the lines Hα λ6563 and [N II] λ6584. The combination of good spatial resolution and signal-to-noise of this dataset makes it ideal for detecting the faint arcs against the varying nebular background. For regions in the outskirts of the nebula that are outside of the GO 9825 fields, we used observations with the same camera and filter from the 104-orbit Cycle 13 program GO 10246 (*HST* Treasury Program on the Orion Nebula Cluster, Robberto et al. 2013). In addition, we have used images from the same program obtained with the F656N filter of the WFPC2 camera. The resolution[1] and signal-to-noise of these observations is significantly worse than the ACS images, but they have the important advantage that the WFPC2 F656N filter is considerably narrower ($\approx$ 5 Å) than the ACS F658N filter ($\approx$ 15 Å) and suffers relatively little contamination from [N II]. Finally, for regions in the core of the nebula, we have used older WFPC2 images from programs GTO 5085 (O'Dell & Wong 1996) and GO 5469 (Bally et al. 1998). These offer two advantages for the study of the bowshocks closest to the Trapezium OB stars: shorter exposure times mean that the bright stars are less saturated, and images were obtained in a much wider range of emission line filters.

For each arc, we trace by eye the inner and outer boundaries of the emission line shell and mark along each edge using "point" regions with the SAOimage ds9 program[2], and in addition mark the position of the central star or proplyd (hereafter, central source). These are shown in Figure 1 as yellow crosses, yellow pluses and blue circle for the outer edge, inner edge, and proplyd, respectively, for an illustrative case. We then fit circular arcs to the points, determining the center and radius of curvature R_c of each edge. The fits are carried out with the aid of the python library lmfit[3], which implements a Levenberg–Marquardt curve-fitting algorithm. The initial parameter estimates for each fit are obtained as follows. First, the sky coordinates (α_i, δ_i) of the edge points are converted to polar coordinates with respect to the central source: (r_i, θ_i), where θ is a position angle (degrees counterclockwise from north). After sorting the edge points in θ, the smallest value of r_i, together with its immediate neighbors to either side are used to define a parabola in polar coordinates, the root of whose derivative gives the point (r_0, θ_0) of closest approach of the arc's edge to the central source.[4] The initial estimate for the position of the center of curvature is taken to be the same distance from the central source as the point of closest approach, but on the "other side" of the source: that is at polar coordinates $(r_0, \theta_0 + 180^\circ)$. The sky coordinates of this center of curvature (α_c, δ_c) are the only two formal parameters of the circle fit since the circle radius is estimated on the fly as the mean distance $\langle R_c \rangle$ from (α_c, δ_c) to the individual edge points (α_i, δ_i). Only those edge points satisfying the condition $|\theta_j - \theta_0| \le 90^\circ$ are used in the fit.

3. CATALOG

3.1. *LV knot group*

The LV knot group is an six proplyds set that were discovered by Laques & Vidal (1979), located very close of the

[1] The point spread function is very similar for the two cameras (FWHM $\approx 0.082''$ at Hα), but it is not well-sampled by the larger $0.1''$ pixels of the three WFC chips of WFPC2.

[2] http://ds9.si.edu

[3] https://pypi.python.org/pypi/lmfit/

[4] This technique will fail if the closest edge point does not have a neighbor to one side, that is, if it is at one end of the traced edge. Such a situation is occasionally found when the observed arc is very asymmetric. In this case a parabola is fitted to all of the edge points (r_i, θ_i) in order to determine (r_0, θ_0).

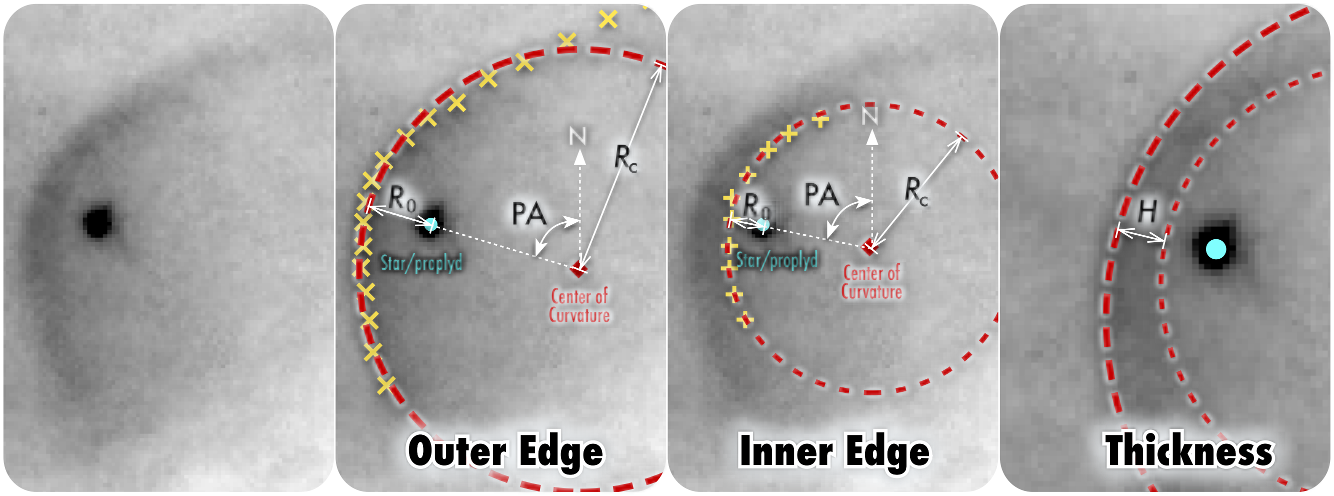

Figure 1. Methodology for determining geometric parameters of the arcs.

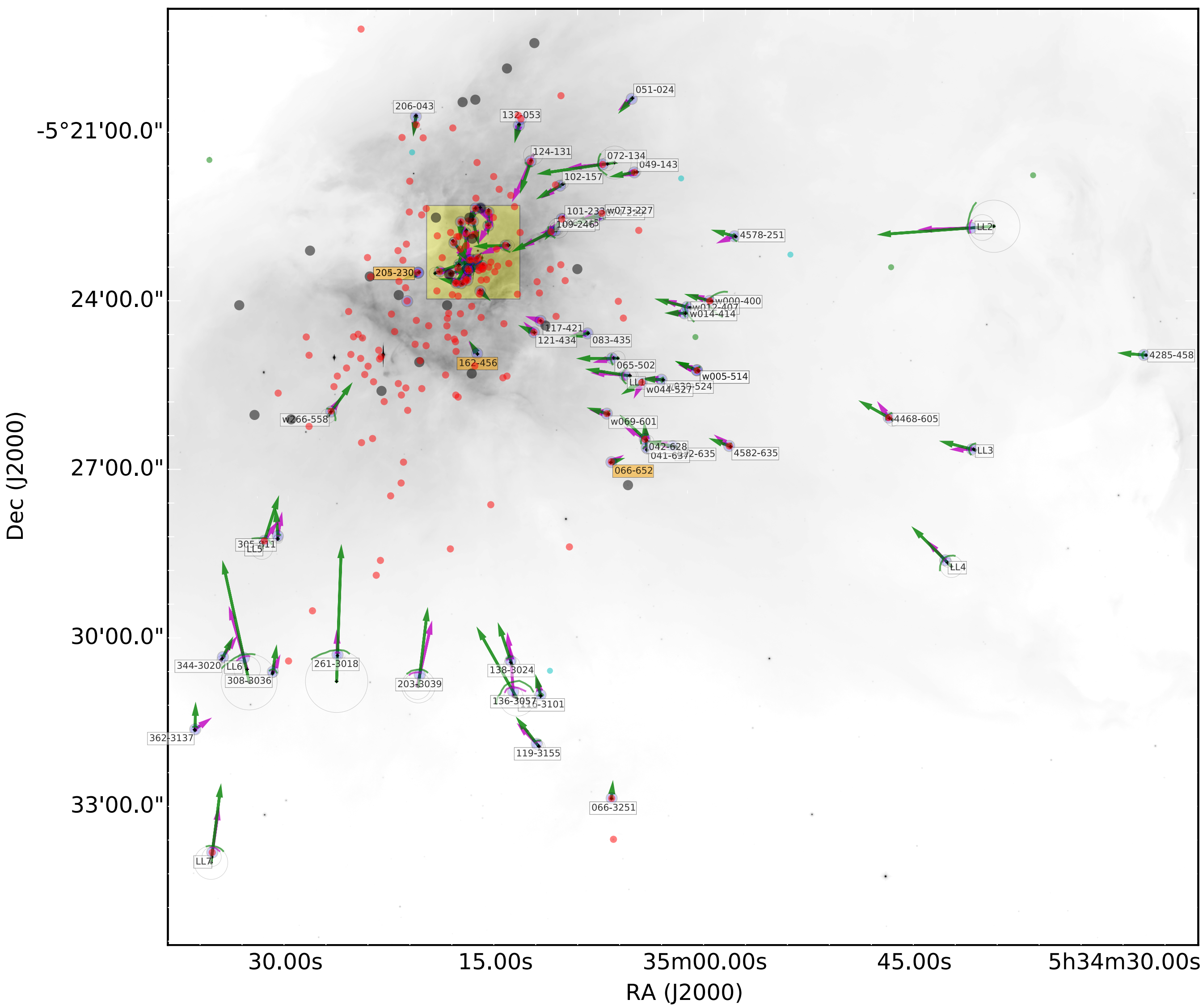

Figure 2. Position of bow shock arcs.

Table 1
Archival *HST* imaging datasets used in this study

Year	Instrument	Program(s)	Field size	Pixel size	Filters
1994–5	WFPC2/WFC	GTO 5085, GO 5469	$5' \times 10'$	$0.1''$	F656N, F658N, F502N, F547M
1994–5	WFPC2/PC	GO 5469	$1' \times 2'$	$0.045''$	F656N, F658N, F502N, F673N, F631N, F547M
2004	ACS/WFC	GO 9825	$20' \times 20'$	$0.05''$	F658N
2004–5	ACS/WFC	GO 10246	$25' \times 30'$	$0.05''$	F658N, F435W, F555W, F775W, F850LP
2004–5	WFPC2/WFC	GO 10246	$25' \times 30'$	$0.1''$	F656N

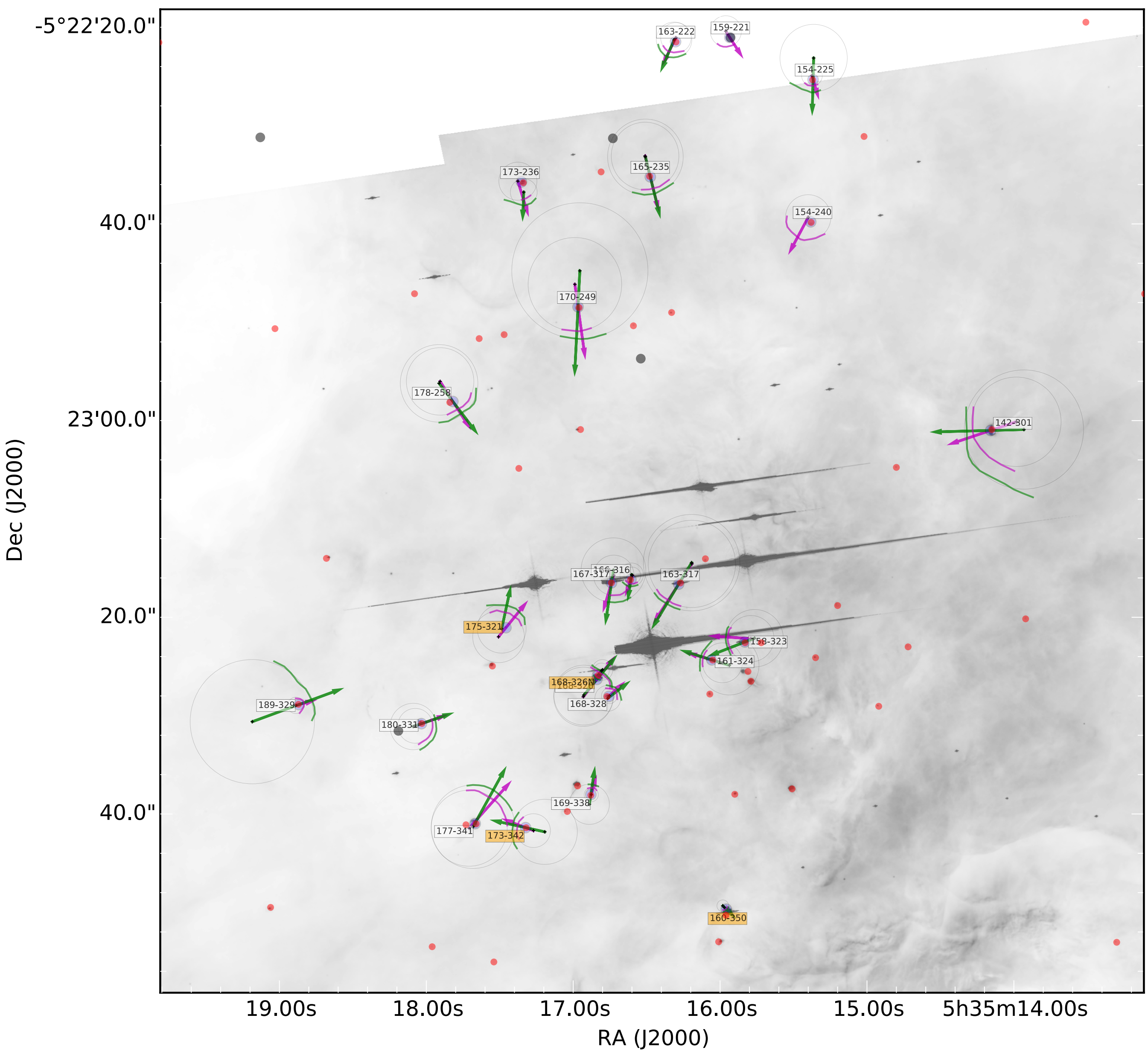

Figure 3. Position of bow shock arcs. Zoomed area.

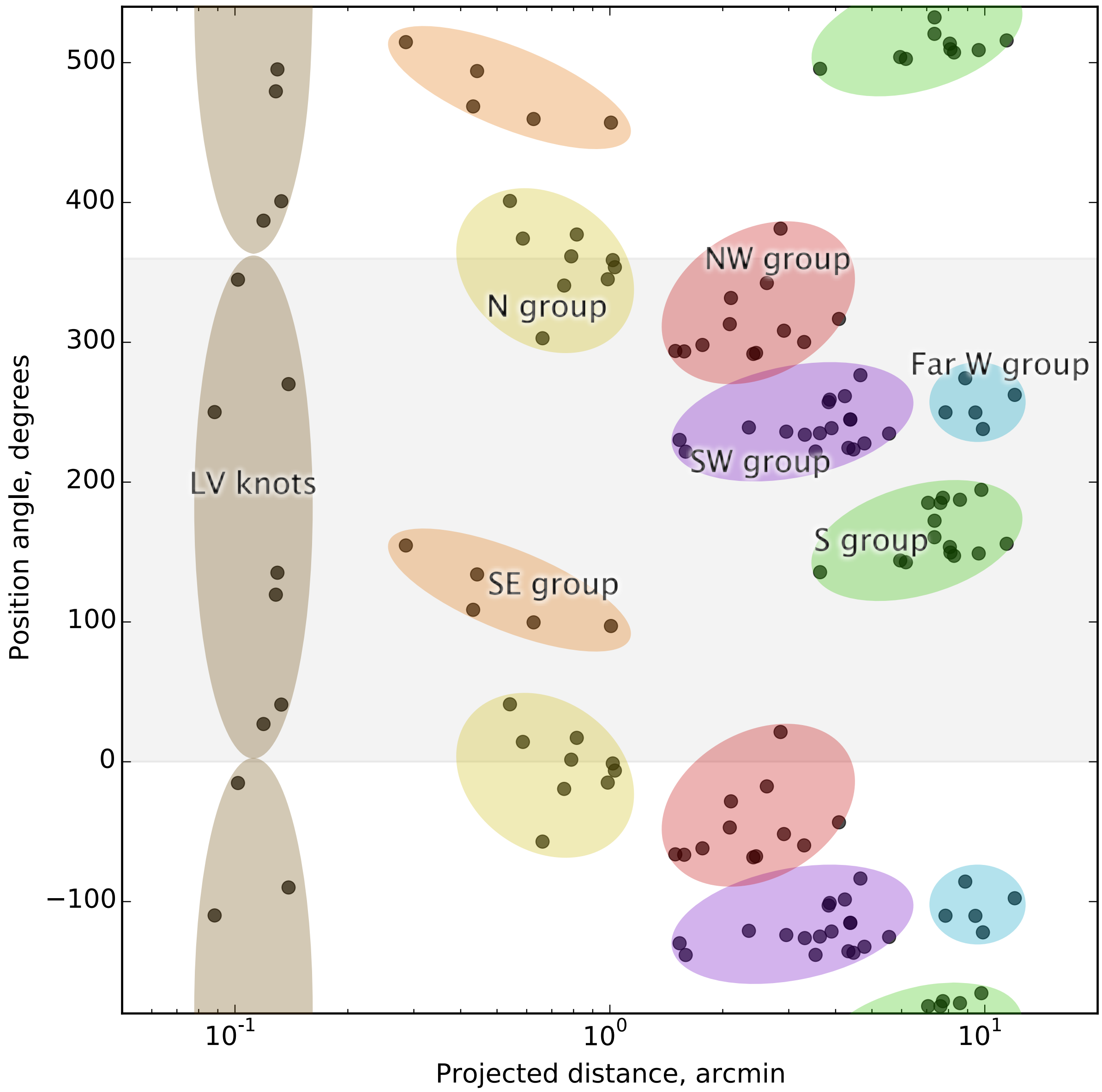

Figure 4. Spatial distribution of the bowshock arcs and classification into spatial groups.

Table 2
Shell geometric parameters of lv knots

Object	RA	Dec	D	PA	$R_{\rm out}$	$R_{\rm in}$	$R_{\rm c,out}$	$R_{\rm c,in}$	h	$\mathrm{PA}_{\rm out}$	$\mathrm{PA}_{\rm in}$
158-323	05:35:15.83	−05:23:22.5	8.34	90.1	1.85	1.64	2.92	2.35	0.21	114.8	120.0
161-324	05:35:16.06	−05:23:24.3	5.29	70.1	1.16	0.90	3.01	2.03	0.26	70.7	76.6
163-317	05:35:16.28	−05:23:16.6	6.11	164.8	2.32	1.93	4.90	4.44	0.40	148.6	145.5
166-316	05:35:16.61	−05:23:16.2	7.15	207.0	0.69	0.41	1.19	0.85	0.28	181.4	160.5
167-317	05:35:16.74	−05:23:16.5	7.97	220.9	1.96	1.25	3.29	2.05	0.71	178.1	165.4
168-328	05:35:16.76	−05:23:28.1	7.79	315.2	1.06	0.79	1.31	0.80	0.27	345.3	353.0
168-326	05:35:16.84	−05:23:26.3	7.71	299.5	0.95	0.74	3.04	3.01	0.20	314.5	328.1

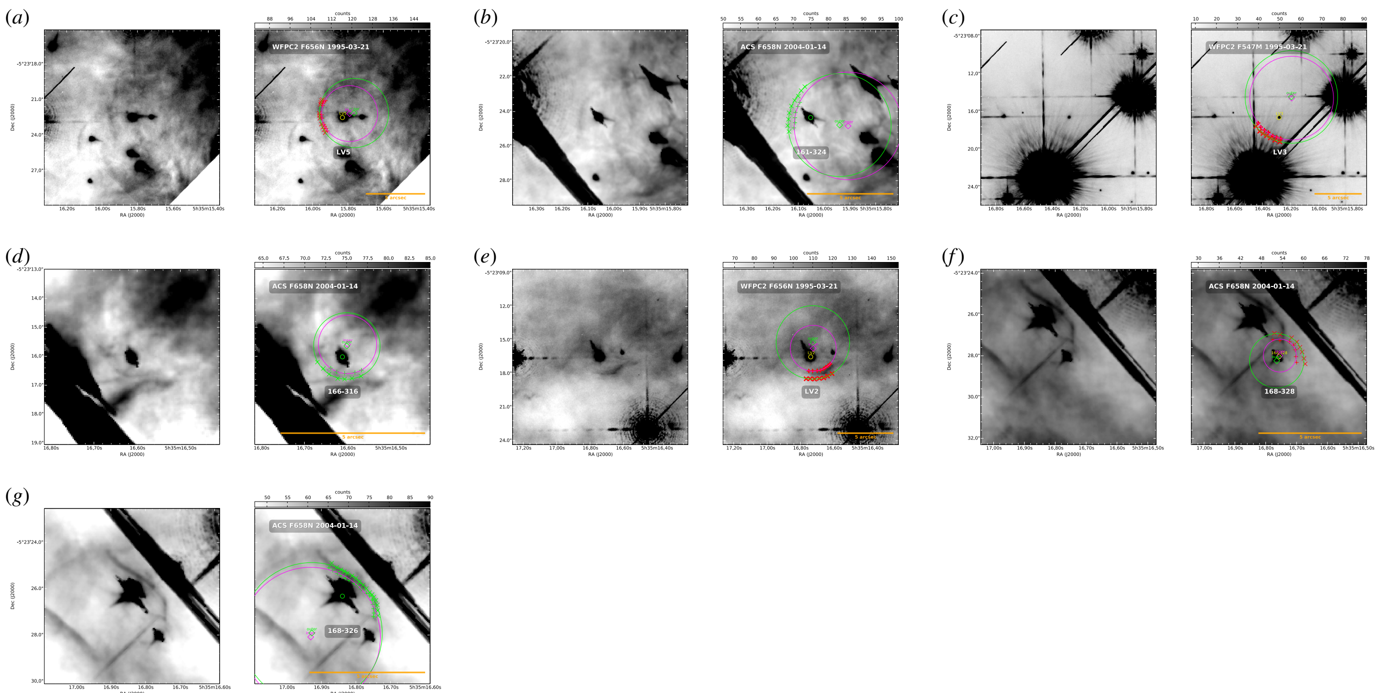

Figure 5. Stationary arc sources in the LV knots group.

Trapezium and show an isotropic distribution. There is a binary system in this group. The emission arcs were identified after. In general, these arcs are very weak, which makes it difficult to trace the edges of the shells.

158-323 (LV5). This was previously catalogued as a round head with tail by O'Dell & Wong (1996). After, it was reported as a proplyd and binary system by (Ricci et al. 2008). An emission arc wraps around this proplyd.

161-324 (LV4). This small and bright proplyd was previously catalogued by O'Dell & Wong (1996); Ricci et al. (2008). The proplyd is surrounded by a faint but well-defined emission arc. This is located about $4.0''$ to the southeast of 158-323.

163-317 (LV3). This proplyd previously catalogued by O'Dell & Wong (1996); Ricci et al. (2008) is surrounded by a faint and small emission arc.

166-316. (LV2b) This was reported as a circularly symetric source by O'Dell & Wong (1996). Later, this source was catalogued as a proplyd by Ricci et al. (2008).

167-317 (LV2). This bright proplyd was previously catalogued by O'Dell & Wen (1994); Ricci et al. (2008). It exhibits a long tail. An obvious emission arc (Bally et al. 2000) wraps around the proplyd. Bally et al. (2000) describe a compact microjet emerging from this proplyd.

168-328. This small proplyd was previously reported by O'Dell & Wen (1994) and Ricci et al. (2008). An emission arc is associated with this proplyd. The arc is much fainter than the proplyd. This object is located about $2.1''$ to the southwest of LV1.

168-326 (LV1). This is a previously reported proplyd designated 168-326S (O'Dell & Wen 1994). This proplyd was classified as a binary system by Ricci et al. (2008). An arc emision with a complex morphology is surrounded this proplyd.

3.2. *Southeast group*

The southeast group is located to the inside of the Orion Nebula. The central sources of their members are proplyds and their LL arcs associated have not been previously reported in the literature. Their diffuse shells are very thin.

169-338. This is a previously reported proplyd (O'Dell & Wen 1994; Ricci et al. 2008). The small and faint proplyd is associated with a very faint but well-defined emission arc.

177-341 (HST 1). This very large proplyd with a long tail was previously catologed by O'Dell & Wen (1994); Ricci et al. (2008). There is probably a jet that emerges from the proplyd (Bally et al. 2000). We identified a well-defined but faint emission arc associated with this proplyd.

180-331. This was first cataloged as a star by O'Dell & Wong (1996). Later, this was reported as a proplyd and a binary system by Ricci et al. (2008). The proplyd is surrounded by a highly asymmetric emission arc.

189-329. The central source was classified as star by O'Dell & Wong (1996). After, Ricci et al. (2008) reported to this source as a proplyd. This object is a very faint proplyd associated with a very diffuse shell. The northern bow wing is much more extended than the southern wing. The fact that the shell is so large and diffuse, may be an indication that it is not related to the proplyd, although the fact that a small cavity is seen around the proplyd suggests that some degree of physical interaction is indeed occurring.

3.3. *North group*

The north group is located inside of the orion Nebula.

142-301. This was previously catalogued as cusp with tail (O'Dell & Wong 1996). Later, this source was classified as proplyd by Bally et al. (2000) and Ricci et al. (2008). This large proplyd has one of the longest tails ($4''$) of any proplyd and does not have a hemispherical head . Instead, the ionization front appears to trace the disk surface, which is inclined with respect to the tail by about 55°. The proplyd tail points away from θ^1 Ori A instead of θ^1 Ori C and exhibits some bends and wiggles (Bally et al. 2000). This proplyd is surrounded by very faint emission arc. Rather than showing continuous curvature, the emission arc appears to comprise two straight edges, which meet at a point south-east of the proplyd, with the shell being thicker on the southern side. The bowshock has not been previously reported in the literature.

154-225. This is a previously catalogued as a elongated with diffuse boundary (O'Dell & Wong 1996). Later, it was reported was as a proplyd and a binary sytem by Ricci et al. (2008). The central source is sorrounded by a very faint emission arc. This emission arc has not been previously reported in the literature. The shell is lumpy.

154-240. This large proplyd was previously reported by Bally et al. (2000) and Ricci et al. (2008). The tail of this bright proplyd has a lenght nearly $3''$ and the protoplanetary disk is inclined seen in silhouette (Bally et al. 2000). We identified a emission arc associated with this proplyd. The inner edge of the shell is well-defined but is difficult to distinguish the outer edge of the shell.

159-221. This was first classified as a star by O'Dell & Wong (1996). This same source was reported as a dark disk seen only in silhouette by Ricci et al. (2008). But a faint emission rim can be seen surrounding the disk in the Hα image, suggesting that it is an externally ionized proplyd. We identified a previously uncatalogued emission arc associated with the central star. The outer edge of the shell is very diffuse, which makes it difficult to trace of outer rim. The axis of the bowshock is significantly deviates from the radial direction.

163-222. This proplyd was first catalogued by O'Dell & Wong (1996). There is a compact $0.''15$ diameter disk seen nearly in face-on embedded in this stubby proplyd (Bally et al. 2000; Ricci et al. 2008). This source was also reported as a binary sytem (Ricci et al. 2008). A previously uncatalogued emission arc wraps around the proplyd. The emission arc is very faint and small, but the outer and inner edges of the shell are well-defined on the eastern side. The western side of the arc is superimposed on an unrelated a brighter larger scale emission filament, making impossible to trace the arc boundaries on this side.

165-235. This was previously catalogued as a star by O'Dell & Wong (1996). Later, It was classified as proplyd by Ricci et al. (2008). This proplyd is sorrounde by a previously uncatalogued emission arc. This emission arc is very faint.

170-249. This is a previously catalogued proplyd O'Dell & Wong (1996); Ricci et al. (2008), which is sorrounded by a very faint emission arc. Ricci et al. (2008) reported the source as a binary system. This bright and large proplyd exhibits a long tail and an inclined disk seen in silhouette (Bally et al. 2000). Several filamentary emission features with arc shape to crosses of the object.

173-236. This large bright proplyd was previously catalogued by O'Dell & Wong (1996) and Ricci et al. (2008). This proplyd was also catalogued by Bally et al. (2000) and designated 174-236. The proplyd with an irregular and wavy tail (see Bally et al. 2000) is surrounded by a very faint emission arc. This emission arc has not been previously reported in the literature.

178-258. This large and weak proplyd was catalogued by

Table 3
Shell geometric parameters of southeast group

Object	RA	Dec	D	PA	$R_{\rm out}$	$R_{\rm in}$	$R_{\rm c,out}$	$R_{\rm c,in}$	h	$\rm PA_{out}$	$\rm PA_{in}$
169-338	05:35:16.88	−05:23:38.0	17.14	334.7	1.03	0.68	2.04	0.72	0.35	345.9	6.4
177-341	05:35:17.67	−05:23:41.0	26.54	314.0	3.81	3.06	4.25	3.87	0.75	317.0	293.7
180-331	05:35:18.03	−05:23:30.8	25.91	288.7	1.44	1.11	2.36	1.77	0.33	280.8	282.0
189-329	05:35:18.87	−05:23:28.9	37.56	279.7	1.40	0.54	6.32	0.83	0.86	296.4	264.0

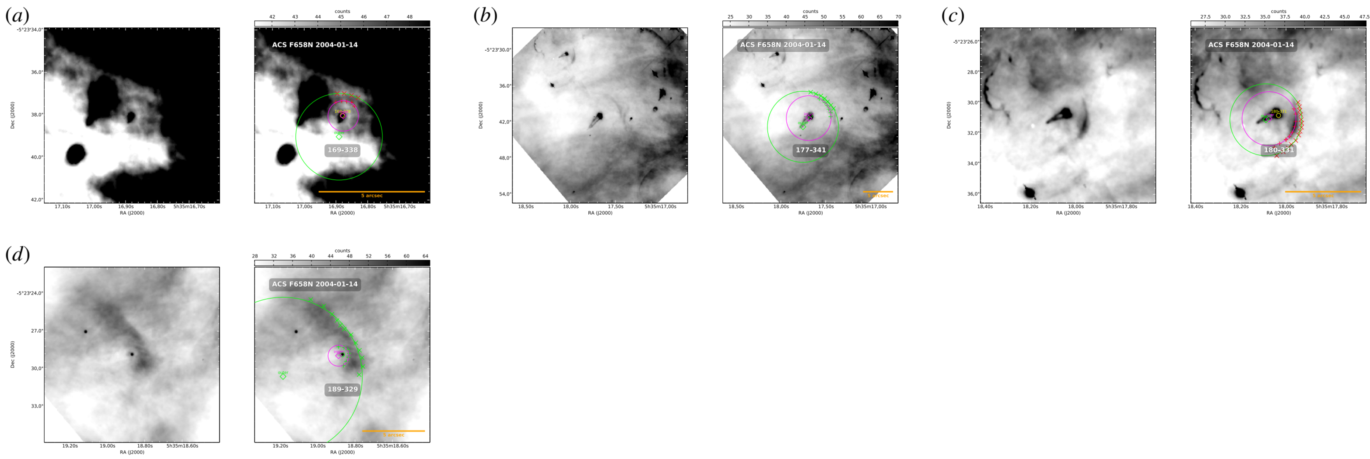

Figure 6. Stationary arc sources in the Southeast group.

Table 4
Shell geometric parameters of north group

Object	RA	Dec	D	PA	$R_{\rm out}$	$R_{\rm in}$	$R_{\rm c,out}$	$R_{\rm c,in}$	h	$\rm PA_{out}$	$\rm PA_{in}$
142-301	05:35:14.16	−05:23:01.0	39.67	122.9	2.42	1.82	6.06	4.55	0.60	91.5	98.6
154-225	05:35:15.37	−05:22:25.3	59.22	165.1	1.29	0.64	3.42	1.05	0.58	158.0	193.1
154-240	05:35:15.38	−05:22:39.8	45.30	160.6	· · ·	1.72	· · ·	2.30	· · ·	· · ·	202.3
159-221	05:35:15.93	−05:22:21.0	61.86	173.7	· · ·	0.83	· · ·	1.58	· · ·	· · ·	215.4
163-222	05:35:16.30	−05:22:21.5	61.07	178.8	1.54	1.11	1.80	1.55	0.36	198.9	180.1
165-235	05:35:16.48	−05:22:35.2	47.33	181.5	1.78	1.23	3.84	3.44	0.47	197.5	193.2
170-249	05:35:16.97	−05:22:48.4	35.16	194.2	3.23	2.45	6.92	4.75	0.78	173.4	193.3
173-236	05:35:17.35	−05:22:35.7	48.96	197.1	2.28	1.53	1.36	1.94	0.75	255.3	275.5
178-258	05:35:17.82	−05:22:58.1	32.47	221.1	1.48	0.92	3.94	3.43	0.52	218.7	210.3

Ricci et al. (2008), which is surrounded by a well-defined but faint emission arc.

3.4. *Northwest group*

The bowshock northwest group is located to the outskirt of the Orion Nebula. The mostly the emission arcs this group have been reported in the literature, with the exception of the 073-227 arc, which it was already previously reported.

4578-251. This is a very bright T Tauri star associated with an emission arc, presents a double-shell morphology. This object has an asymmetric bow shock and the shell is more extended toward the south. The emission of the outer shell is fainter than the inner shell and is unclear whether the region marked with points is part of the outer shell. This emission arc has not been previously reported in the literature.

049-143. Figure shows a proplyd with a very diffuse arc of emission. Its shell is thick, the wings of the bow shock are very open, and circular shaped. The inner edge is more diffuse than the outer edge and the bow is asymmetric. The proplyd has a short tail, probably indicating that it is highly inclined and there is extinction in the center. The emission arc has not been previously reported in the literature.

051-024. We identified a previously uncataloged proplyd with its bow shock located in front of the upper end of the North Bright Bar, their shocks are aimed at Trapezium, is one of the farthest object from the Trapezium in this group. The emission shell is thin, but a second larger, and more diffuse, emission shell is seen in front of the bow shock that we have marked. It is unclear whether this outer shell is related to the object or not. If it is true the object would be similar to the nearby 072-134. The emission arc has not been previously reported in the literature.

072-134. This is a large proplyd surrounding an edge-on disk seen in extintion associated with an emission arc. This object is located to the south east from 051-134. It was first cataloged by O'Dell & Wong (1996) and it was designated 072-135. This proplyd was also reported and decribed by Bally et al. (2000). Later, Ricci et al. (2008) listed a disk seen

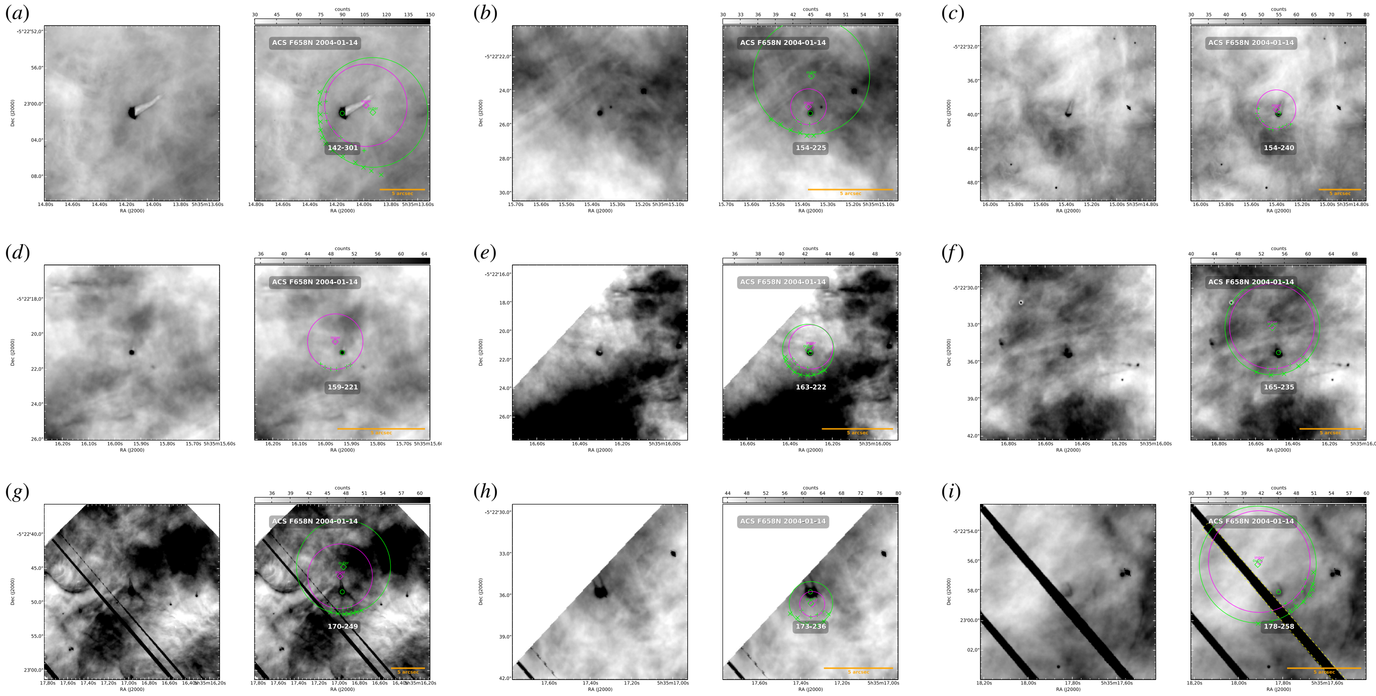

Figure 7. Stationary arc sources in the North group.

Table 5
Shell geometric parameters of northwest group

Object	RA	Dec	D	PA	$R_{\rm out}$	$R_{\rm in}$	$R_{\rm c,out}$	$R_{\rm c,in}$	h	$\rm PA_{out}$	$\rm PA_{in}$
4578-251	05:34:57.79	−05:22:51.1	279.49	96.5	1.85	1.19	3.52	2.07	0.53	81.2	125.0
049-143	05:35:04.94	−05:21:42.9	197.82	120.2	1.17	0.62	4.18	0.66	0.56	103.1	139.0
051-024	05:35:05.13	−05:20:24.3	245.01	136.7	1.19	0.90	2.29	1.66	0.27	136.5	123.6
072-134	05:35:07.20	−05:21:34.3	174.74	128.3	4.69	2.26	17.63	7.29	2.42	89.7	94.5
w073-227	05:35:07.27	−05:22:26.5	147.27	112.4	1.63	0.81	6.46	3.98	0.70	117.0	120.5
074-229	05:35:07.38	−05:22:28.9	144.78	111.7	1.36	0.79	1.60	0.75	0.60	120.3	185.7
101-233	05:35:10.13	−05:22:32.6	105.94	118.1	2.46	2.11	4.36	4.21	0.42	131.4	136.6
102-157	05:35:10.25	−05:21:57.1	125.30	133.0	0.80	0.40	5.03	3.54	0.45	118.5	116.6
106-245	05:35:10.58	−05:22:44.7	94.70	113.5	0.63	0.23	2.48	1.12	0.38	122.7	99.0
109-246	05:35:10.90	−05:22:46.3	89.68	113.8	1.95	1.32	10.64	7.33	0.70	112.9	119.5
124-131	05:35:12.38	−05:21:31.4	126.20	151.7	4.48	2.74	5.95	10.41	1.73	134.9	156.0
132-053	05:35:13.20	−05:20:52.6	157.31	162.4	0.72	0.32	1.80	0.68	0.39	153.9	167.0
206-043	05:35:20.56	−05:20:43.1	171.16	201.3	1.61	1.12	2.19	2.08	0.44	176.1	182.7

nearly edge-on, also named 072-135. It is shell has a complex morphology with a narrow bright arc at the inner edge, together with a much a thicker and fainter shell, which is only visible on the N side.

073-227. Bally et al. (2000) reported a wind collision front associated with 073-227. The well-defined outer edge of the arc deviates significantly from the circular fit in the south wing of the bowshock.

074-229. This is located at south east of 073-227, it is a T Tauri star associated with a small and faint emission bow shock. It appears to be a smaller twin of the nearby 073-227. The central star is not obviously a proplyd, but this may be because it is too small to be resolved. The emission arc has not been previously reported in the literature. The projected separation from 072-134 is about $8''.0$, which is not significantly smaller than the expected mean projected separation between nearest neighbors given the stellar density at this distance from the Trapezium (cite). However, given that only $\simeq 30\%$ of the star in the ONC show emission arcs, the fact that 074-229 and 073-227 both show arcs means that it is likely the form a physical binary-system.

101-233. This is a first cataloged proplyd by O'Dell & Wong (1996), designated 102-233, associated with a bow shock. Later, This proplyd was also cataloged by Ricci et al. (2008). Its cumply shell is thin and low ionization. Furthermore, this object has a clumpy shell. Several addititional broad filamentary emission features can be seen in front of the arc, but it is unclear if these are associated with the object or are a chance superposition, that also seem to be aimed toward Trapezium. The emission arc has not been previously reported in the literature. [There are references?]

102-157. We identified a previously uncataloged proplyd associated with a very faint emission arc. The proplyd tail is very short, indicating that it is highly inclined. 102-157 has a open bow. The southwest wing of the bowshock is crossed by an apparently unrelated east-west oriented filament, which

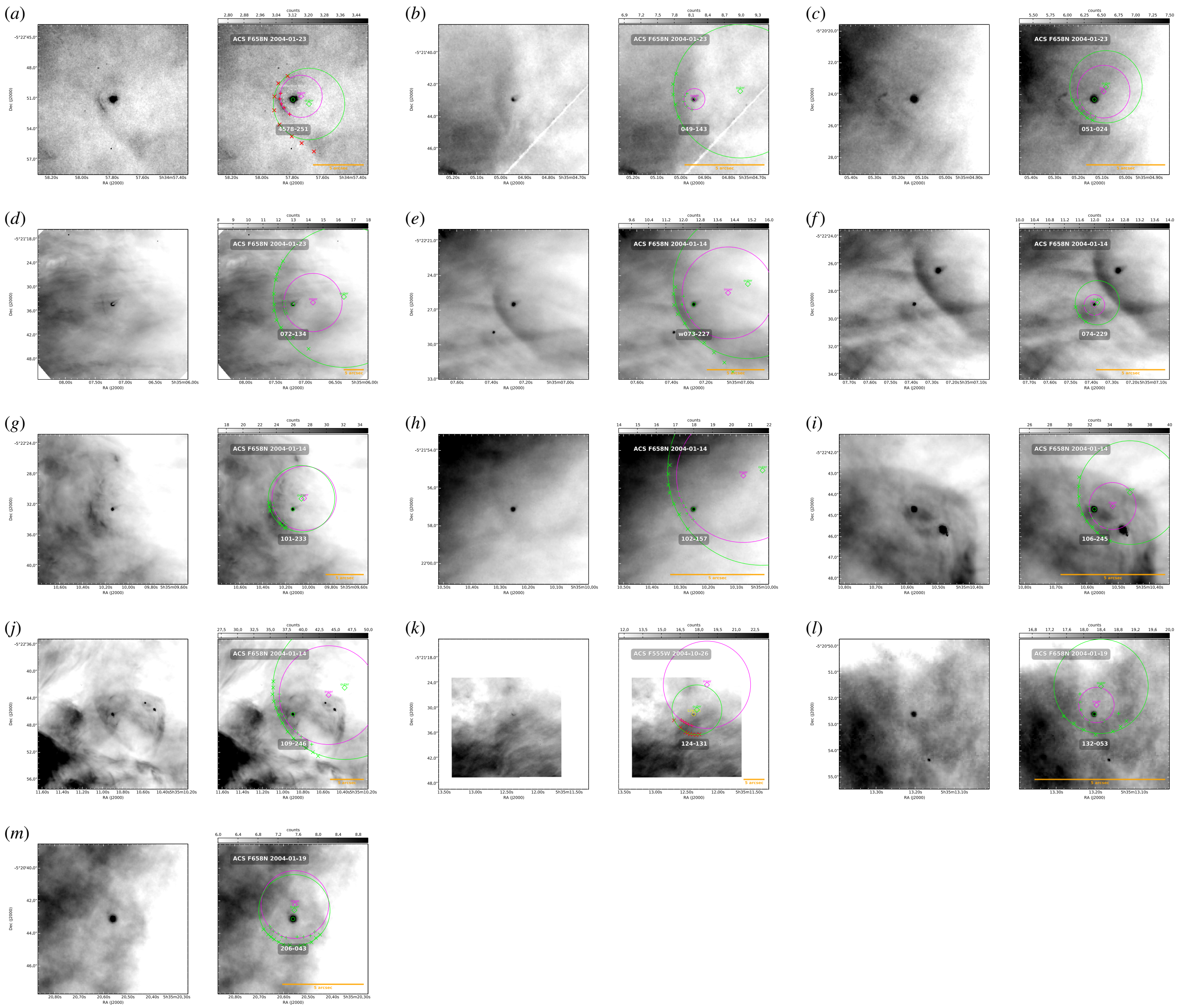

Figure 8. Stationary arc sources in the Northwest group.

makes it difficult to trace the emission arc on this side. The emission arc has not been previously reported in thee literature.

106-245. Another previously uncataloged proplyd associated with an emission arc candidate, was identified just outside HH 202 and designated 106-245. It is the second smallest arc in this group. The emission arc has not been reported previously in the literature.

109-246. Bally et al. (2000) reported a proplyd possibly associated with yet knots, which they designated 109-247, but we have 109-246, based on the accurate position. This object is located a south east from 106-245, almost in front of the 106-245 shock's. This object is within a complex region of the nebula, just outside the principal bowshock of HH 202. A chain of faint W-facing bowshocks, which may be associated with HH 202, crosses the object but the feature that we identify as the stationary emission arc is different from these since it faces ESE. The wings of the emission arc are very open.

124-131. This object is a circumbinary proplyd, that was first cataloged by O'Dell & Wong (1996), but they named it 124-132 and classified it as irregular. It was also cataloged by Ricci et al. (2008), they mention that 124-131 is a binary system and that it has a jet. Robberto et al. (2008) reported on the discovery of the circumbinary proplyd seen in silhouette against the bright background of the Orion Nebula, they show that 124-132 is a photoevaporated disk that harbors a binary system. This source was also reported by Smith et al. (2005), they show a microjet emerging perpendicular to the major axis of the disk. Figure shows a very faint emission arc, which is not detected in Hα but only in green and blue wideband filters, suggesting that we are seeing dust-scattered continuum.

206-043. Arc candidate. This object is a bright star associated with a very faint emission bow, the arc is quite narrow. It is the closest object to the north Bright Bar in this group. It has not been previously reported in the literature. A filamentary dark cloud is located $3''.0$ to west, and the apparent arc may be an ilusion caused by extension of these extinction filaments.

3.5. *Southwest group*

The bowshock southwest group is located to the outskirts of the Orion Nebula. The mostly of its members are the tipycal LL Ory arcs, with its well-defined emission arc.

4582-635. This is a previously cataloged proplyd (Ricci et al. 2008), which is surrounded by a very faint arc of emission. The faint emission arc has not been reported previously in the literature. There are hints of additional emission knots in front of the arc, but the S/N is very low and it is unclear if they are related with the object.

000-400. Bally et al. (2000) reported a wind collision fronts associated with w000-400. The central source is a previously catalogued proplyd, designated 4596-400 (Ricci et al. 2008). The outer edge of the wings of the emission arc can be traced to much farther distances than is typical, at least 5 times the axial radius of curvature. The northern wing becomes knotty at large distances, where the southern wing is smoothes. The bow shock has parabolic morphology and wraps around a proplyd (Fig.).

005-514. This proplyd was first cataloged by O'Dell & Wong (1996). Later, Bally et al. (2000) reported a fainter and smaller wind-wind collission front, designated w005-514 and was show in Hα image. The lower (southeast) wing of the arc has a complex structure, with multiple overlapping filaments.

012-407. Bally et al. (2000) reported a wind collision fronts associated with 012-407. The bright central star is not obviously a proplyd. The diffuse shell is very thick.

014-414. Bally et al. (2000) cataloged another wind collision front associated with 014-407. It is one of the smaller LL arcs in this group, containing a double central star. A larger scale filament which is prominent in blue/green continuum crosses the object, but seems to be unrelated.

022-635. This is a previously uncataloged arc of emission that wraps around a T Tauri star. The north wing of the bowshock is more extended than south wing. There are two apparently unrelated emission filaments that cross this object.

030-524. Bally et al. (2000) reported a wind-wind collision front, associated with w030-524. The central source has a tail oriented away from the Trapezium, indicating a proplyd. The northern outer edge of the asymmetric shell is very flat and it makes a sharp corner where it joins the head of the shell.

041-637. This is a previously reported star (Da Rio et al. 2009) associated with a faint emission arc. There is a west faint emission arc, which is probably unrelated to the object. The emission arc has not been previously reported in the literature.

042-628. This object was classified as proplyd by Ricci et al. (2008), designated 038-627. One clearly sees a previously uncataloged emission arc that wraps around this proplyd, with well defined edges. The shell shape and size are very similar to LL 1, but it is ten times fainter and lacks any evidence for a jet.

044-527. A faint and small emission arc associated with 044-527 was cataloged by Bally et al. (2000). The central source was subsequently classified as proplyd by Ricci et al. (2008). This object has a jet parallel to the proplyd axis. The bowshock is very asymmetric.

LL 1 (056-519). The T Tauri star LL Orionis is the prototype of the LL objects. Its emission arc was discovered by Gull & Sofia (1979) and is now denoted LL 1. This is a parabolic or hyperbolic bowshock that wraps around the source star (Bally et al. 2006). This emission arc was also reported by Bally et al. (2000) and as a LL Orionis-type wind-wind collision fronts LL 1 by Bally & Reipurth (2001). The emission of the bowshock wings is blueshifted with repect to the backgraond nebular emission, the emission from the head of the bowshock is at a similar velocity to the nebula and shows no detectable proper motion, consistent with it being a stationary structure (Henney et al. 2013). LL 1 is associated with a hypersonic jet Herbig-Haro, HH 888, that arises in the T Tauri star.

065-502. This was classified as a non-proplyd stellar source by O'Dell & Wong (1996). This star has a small protrusion which points away from Trapezium, probably indicating a proplyd tail. This proplyd tail is very short, suggesting that it is highly inclined. The source is surrounded by a very faint emission arc, which has not been previously reported in the literature. This object is located $\approx 22.0''$ to the northeast of LL 1.

069-601. This was first classified as a non-proplyd stellar source by O'Dell & Wong (1996). Later, a wind collision front was reported by Bally et al. (2000) associated with w069-601. Ricci et al. (2008) catalogued the central source as a proplyd. The parabolic arc emission is well-defined, which makes it easy to trace the edges of the shell. The arc shape is very similar to LL 1, but is considerably smaller.

117-421. This was previously classified as a non-proplyd stellar source by O'Dell & Wong (1996). Later, this same object was catalogued as proplyd by Ricci et al. (2008). We identified a small and very faint emission arc, that wraps around this small proplyd.

121-434. This is a previously catalogued proplyd (Ricci et al. 2008), which is surrounded by a compact emission arc. The arc emission has not been previously reported in the literature.

3.6. *West group*

This sparsely populated group is located in the outskirts of the Orion Nebula.

4285-458. This is a previously unreported star associated with an emission arc. Although the outer boundary of the shell is well-defined, it is impossible to trace the shell's inner boundary due to confusion with the PSF wings of the central star. The LL arc has not been previously reported in the literature. It is the most distant emission arc from the Trapezium in this catalog. It is also much smaller than the other arcs in the west group.

LL 3 (4408-639). This is a previously reported LL Ori-type object (Bally & Reipurth 2001). An obviuos emission arc wraps around a bright star. This object exhibits a double-shell morphology. A faint emission structure protudes from the central star to the WSW, which may represent a proplyd tail, although the object has not previously been cataloged as a proplyd, similar to several sources in the northwest group.

LL 2 (4409-242). This LL Ori-type object (Bally & Reipurth 2001), is associated with the star IX Ori. This object has a bipolar jet HH 505, which is oriented nearby perpendicular to the bowshock axis. Apart from LL 1, this is the only LL object whose kinematics have been studied via spectroscopic mapping. Unlike LL 1, the structure and kinematics of the LL arc are very asymmetrical (Henney et al. 2013). Only the head and northern wing of the arc are stationary structures. The southern portion of the arc has high proper motion and seems to be driven by the blueshifted jet.

LL 4 (4427-838). This is a previously reported LL Ori-type object (Bally & Reipurth 2001). The central source was reported as a proplyd and a binary system by Bally et al. (2006). At first glance, this object appears to be a single arc with a very large radius of curvature. However wide closer inspection suggests that the "wings" of the arc are separate structures

Table 6
Shell geometric parameters of southwest group

Object	RA	Dec	D	PA	$R_{\rm out}$	$R_{\rm in}$	$R_{\rm c,out}$	$R_{\rm c,in}$	h	$\rm PA_{out}$	$\rm PA_{in}$
4582-635	05:34:58.17	−05:26:35.1	333.37	54.7	1.11	0.68	2.93	2.06	0.46	65.7	50.5
w000-400	05:34:59.57	−05:24:00.1	254.03	81.5	1.47	0.80	4.37	2.43	0.68	71.9	73.4
w005-514	05:35:00.47	−05:25:14.3	262.72	64.8	1.65	1.20	3.45	2.03	0.44	64.5	57.9
w005-514	05:35:00.47	−05:25:14.2	262.64	64.8	1.67	1.17	2.24	2.21	0.42	91.0	56.9
w012-407	05:35:01.17	−05:24:06.7	231.47	79.0	2.29	0.95	6.74	4.26	1.23	68.3	69.7
w014-414	05:35:01.37	−05:24:13.4	229.95	77.2	1.21	0.37	2.19	1.61	0.70	98.3	93.2
022-635	05:35:02.20	−05:26:35.3	286.47	47.7	1.10	0.75	4.46	2.29	0.34	83.2	77.5
w030-524	05:35:03.00	−05:25:24.4	234.09	58.6	0.63	0.29	2.56	1.54	0.32	93.8	82.0
041-637	05:35:04.06	−05:26:37.1	267.84	43.4	1.94	1.19	4.39	3.23	0.77	4.2	15.5
042-628	05:35:04.20	−05:26:27.6	259.59	44.5	3.07	1.76	6.90	3.61	1.34	61.6	56.1
w044-527	05:35:04.43	−05:25:27.4	217.94	55.0	2.13	0.78	3.25	1.53	0.85	121.2	267.4
LL1	05:35:05.64	−05:25:19.4	198.63	53.9	3.06	1.90	8.72	7.13	1.13	84.4	78.1
065-502	05:35:06.54	−05:25:01.5	177.29	56.1	1.42	0.49	7.74	2.31	1.21	90.5	104.7
w069-601	05:35:06.91	−05:26:00.6	212.19	41.9	0.85	0.41	2.72	1.77	0.42	86.1	87.1
083-435	05:35:08.29	−05:24:34.9	140.89	59.1	1.25	0.54	2.00	0.66	0.58	84.0	40.5
117-421	05:35:11.65	−05:24:21.4	92.07	50.2	· · ·	0.71	· · ·	0.93	· · ·	· · ·	96.7
121-434	05:35:12.12	−05:24:33.8	95.58	41.8	0.76	0.34	1.41	0.69	0.39	65.4	66.2

Table 7
Notes on Southwest Group

Source	Proplyd	Star	Arc	Notes
4582-635	R08	· · ·	New	Very faint
000-400	R08	· · ·	BOM00	Designated 4596-400 in R08
005-514	OW96	· · ·	BOM00	
012-407	No	· · ·	BOM00	Thick, diffuse arc
014-414	No	· · ·	BOM00	Double central star
022-635	No	· · ·	New	Asymmetric arc
030-524	?	· · ·	BOM00	Flat, asymmetric arc, apparent proplyd tail

Table 8
Shell geometric parameters of west group

Object	RA	Dec	D	PA	$R_{\rm out}$	$R_{\rm in}$	$R_{\rm c,out}$	$R_{\rm c,in}$	h	$\rm PA_{out}$	$\rm PA_{in}$
4285-458	05:34:28.52	−05:24:57.9	721.18	82.4	1.91	· · ·	4.34	· · ·	· · ·	87.0	· · ·
LL3	05:34:40.81	−05:26:38.5	566.33	69.8	3.12	1.28	6.54	3.08	1.83	89.2	99.6
LL2	05:34:40.86	−05:22:42.2	532.12	94.3	4.04	2.07	27.93	13.84	1.13	97.6	89.5
LL4	05:34:42.72	−05:28:37.2	593.11	58.0	2.42	1.42	11.79	4.95	0.99	46.7	40.3
4468-605	05:34:46.76	−05:26:04.8	471.30	69.9	2.47	1.33	7.11	2.22	1.20	54.2	59.6

from the more curved nose region. We propose that they are not part of the true LL arc, but are driven by the bipolar jet (Bally et al. 2006) in a similar way to the southern wing of LL 2.

4468-605. Bally et al. (2006) show a proplyd surrounded by a faint arc of emission with a microjet parallel (HH 886) to the axis of the proplyd and the emission arc. Although Bally et al. (2006) report the jet as one-sided, a bright Hα filament seen at the end of the proplyd tail many represent the counterjet. Figure shows that the arc of 4468-605 has a flared morphology, although a larger scale filament of emission, which is probably unrelated to the object, is seen in projection against the upper half of the bowshock, which makes it difficult to discern the true shape of the bowshock on this side.

3.7. *South group*

The bowshock south group is located in the outskirts of the Orion Nebula and southeast of the Bright Bar, several members of this group are the farthest objects from the Trapezium. The objects are generally large in this group and many have a bright inner rim.

066-3251. This object was classified as a proplyd by Ricci et al. (2008) and, located at a distance $\sim 10'$ south of the ONC core, it is one of the farthest known proplyds from the Trapezium. We have identified a faint arc associated with this proplyd, which is seen most clearly in the F555W broad band filter but is also visible in the Hα filter. This object is projected onto the tip of a large-scale wishing bone shaped filament, which seems to represent a local ionization front. We believe that the “outflow”, which Ricci et al. (2008) identify to the south of this object is merely a misidentification of part of this filament.

116-3101. Figure shows a proplyd associated with a small

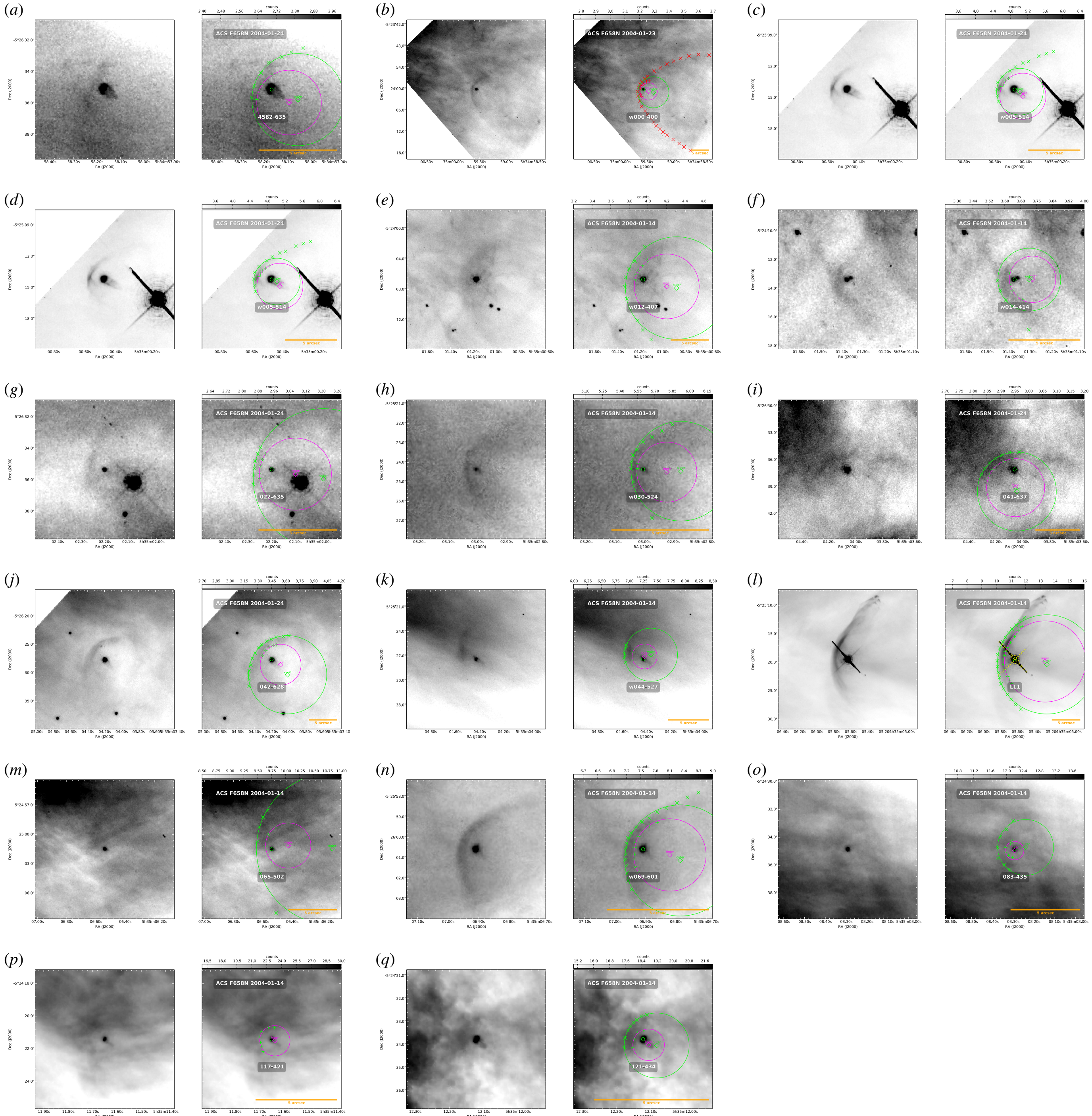

Figure 9. Stationary arc sources in the Southwest group.

but sharply defined emission arc. The central star is also named V488 Ori (Bally et al. 2006). The wings of the bow shock are very closed, the outer edge is well defined and has a circular shape since we can fit a perfect circle with the points marked.

119-3155. This is a binary system associated with an emission arc. Based on the position of the outer of curvature of the arc, we assign the fainter, more northern binary component as the corresponding stellar source. It has a faint arc to the north and another to the east (Fig), but the east arc is probably unrelated to the object, and may instead be associated with the HH 880 bowshock which passes $15''$ to the south. This emission arc has not been previously reported in the literature.

136-3057. This is a T Tauri star associated with an emission arc. It is located to the north of 119-3155 and is one of the bigger objects of this group. 136-3057 has a very diffuse shell. This has not been previously reported in the literature.

138-3024. Figure shows a T Tauri star associated with a thin shell. The arc is seen most strongly blue and green broad band filters, but it is also seen at very low contrast in the Hα filter. This object has not been previously reported in the literature.

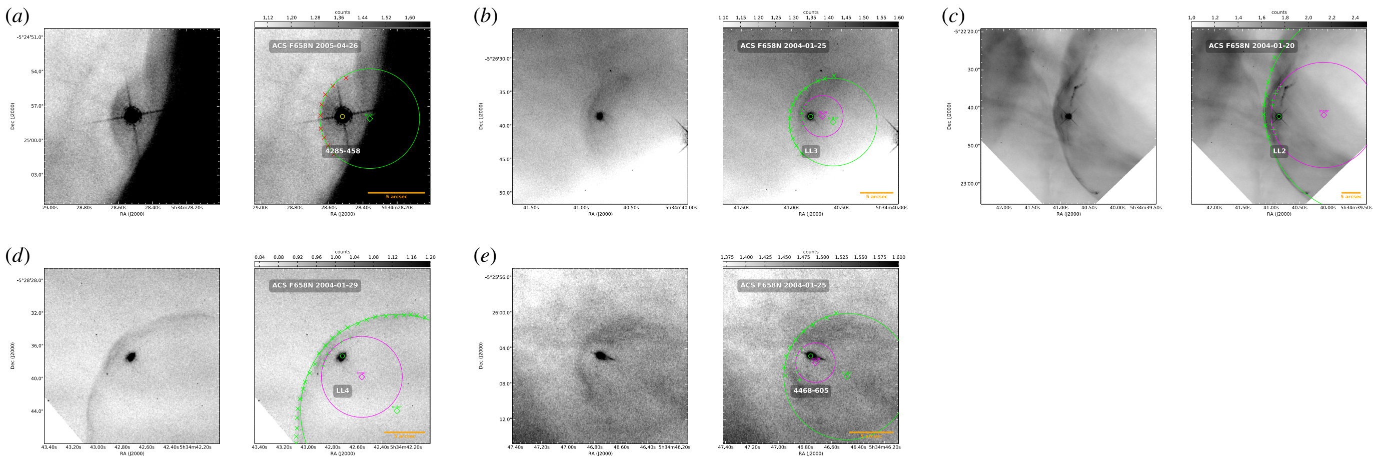

Figure 10. Stationary arc sources in the West group.

Table 9
Shell geometric parameters of south group

Object	RA	Dec	D	PA	$R_{\rm out}$	$R_{\rm in}$	$R_{\rm c,out}$	$R_{\rm c,in}$	h	PA$_{\rm out}$	PA$_{\rm in}$
066-3251	05:35:06.57	−05:32:51.4	587.49	14.5	1.07	···	1.59	···	···	300.1	···
116-3101	05:35:11.65	−05:31:01.0	463.92	8.8	1.45	1.00	2.69	1.57	0.44	24.0	7.9
119-3155	05:35:11.93	−05:31:53.3	515.10	7.4	3.02	1.95	6.73	5.11	1.00	33.3	35.3
136-3057	05:35:13.61	−05:30:57.6	456.93	5.2	10.13	4.91	18.71	10.20	4.51	10.9	4.4
138-3024	05:35:13.80	−05:30:24.4	423.64	5.2	3.89	2.74	8.54	4.79	1.11	22.2	17.4
203-3039	05:35:20.29	−05:30:39.4	440.72	352.4	5.38	1.76	17.90	14.50	3.06	359.4	8.2
261-3018	05:35:26.17	−05:30:18.0	440.40	340.6	4.99	2.51	33.29	3.59	2.59	1.7	357.1
w266-558	05:35:26.62	−05:25:58.3	218.16	315.6	1.88	1.13	7.76	1.51	0.78	330.7	298.5
305-811	05:35:30.44	−05:28:11.2	356.86	324.0	1.72	0.89	4.92	3.99	0.80	358.6	349.7
308-3036	05:35:30.79	−05:30:36.3	484.13	333.6	2.56	1.44	4.50	1.78	1.12	359.9	329.8
LL5	05:35:31.40	−05:28:16.4	369.54	322.7	2.96	1.46	11.58	3.52	1.49	339.7	339.7
LL6	05:35:32.87	−05:30:21.5	485.82	329.6	3.63	1.63	29.90	14.20	2.05	7.6	18.0
344-3020	05:35:34.36	−05:30:20.6	496.76	327.3	1.66	0.67	3.15	4.42	0.95	334.9	325.5
LL7	05:35:35.13	−05:33:49.2	686.23	335.9	7.00	5.53	17.96	10.31	1.46	359.2	3.8
362-3137	05:35:36.35	−05:31:37.8	577.96	329.0	3.12	1.57	4.25	2.22	1.47	6.4	267.8

203-3039. This object has a microjet (HH 561) which was discovered in the Fabry-Pérot study of the southern Orion Nebula by Bally & Reipurth (2001). Later, this HH object was described in more detail by Bally et al. (2006), the microjet emerges toward the east from the variable star MY Ori, terminating in a faint bowshock at a distance of 16″. A fainter counterjet and bowshock are located west of the star. In addition to these previously reported features, we identify an LL-type emission arc associated with MY Ori. The faint bow is very open.

261-3018. This is a relatively large and diffuse LL-type arc previously unreported, seen superimposed on a very complicated region of overlapping flows. We tentatively identify the star 261-3018 as the source, although the star (264-3016) is another possible candidate. In the Hα the 261-3018 star (which is the same source as 262-3018 reported by Bally et al. 2006) shows a linear protrusion of length $\simeq 1''$ towards the southwest. This is unlikely to be a proplyd tail, since it is not aligned with the radial direction from the Trapezium, and instead may be a microjet. Indeed, a series of faint knots and bowshocks extend for 30″ in the same direction. The LL-type arc is very flat and shows a bright rim at its inner edge. It extends further to the east than to the west. The object is seen in projection superimposed on the HH 502 flow but shows no evidence of physical interaction with this flow.

266-558. Bally et al. (2000) catalogued a wind collision front associated with w266-558. Figure shows emission shell that wraps around the source. The source is a previously catalogued proplyd by Ricci et al. (2008). w266-558 presents a double-shell morphology, with knotty bow wings. The bow wings are very open. Although, we have assigned this object to the south group, it is located much closer to the Trapezium than the other members, in a region lacking in other arcs.

305-811. Previously classified as LL-type object by Bally et al. (2006). The emission arc is extremely faint and asymmetric. The star shows a faint protrusion to the southeast in the Hα filter, probably indicating a proplyd tail, although the source has not previously been catalogued as a proplyd.

308-3036. Bally et al. (2006) reported a bright star, that is surrounded by a faint arc of emission, located to the west of LL 6. This object has a nearly circular inner shock, the circle fit is roughly centered on the star. The circular silhouette (see Fig.) may trace a wind cavity, or possibly a dusty envelope surrounding the star (Bally et al. 2006).

LL 5 (315-816). This is a LL Ori type object identified in the outskirts of the Orion Nebula, it was first reported by Bally & Reipurth (2001). Later, it was also catalogued by Bally et al. (2006) and they mentioned that LL 5 is associated with the V1559 Ori star. This object has a short jet (HH 875 Bally et al. 2006) emerging from the proplyd toward the

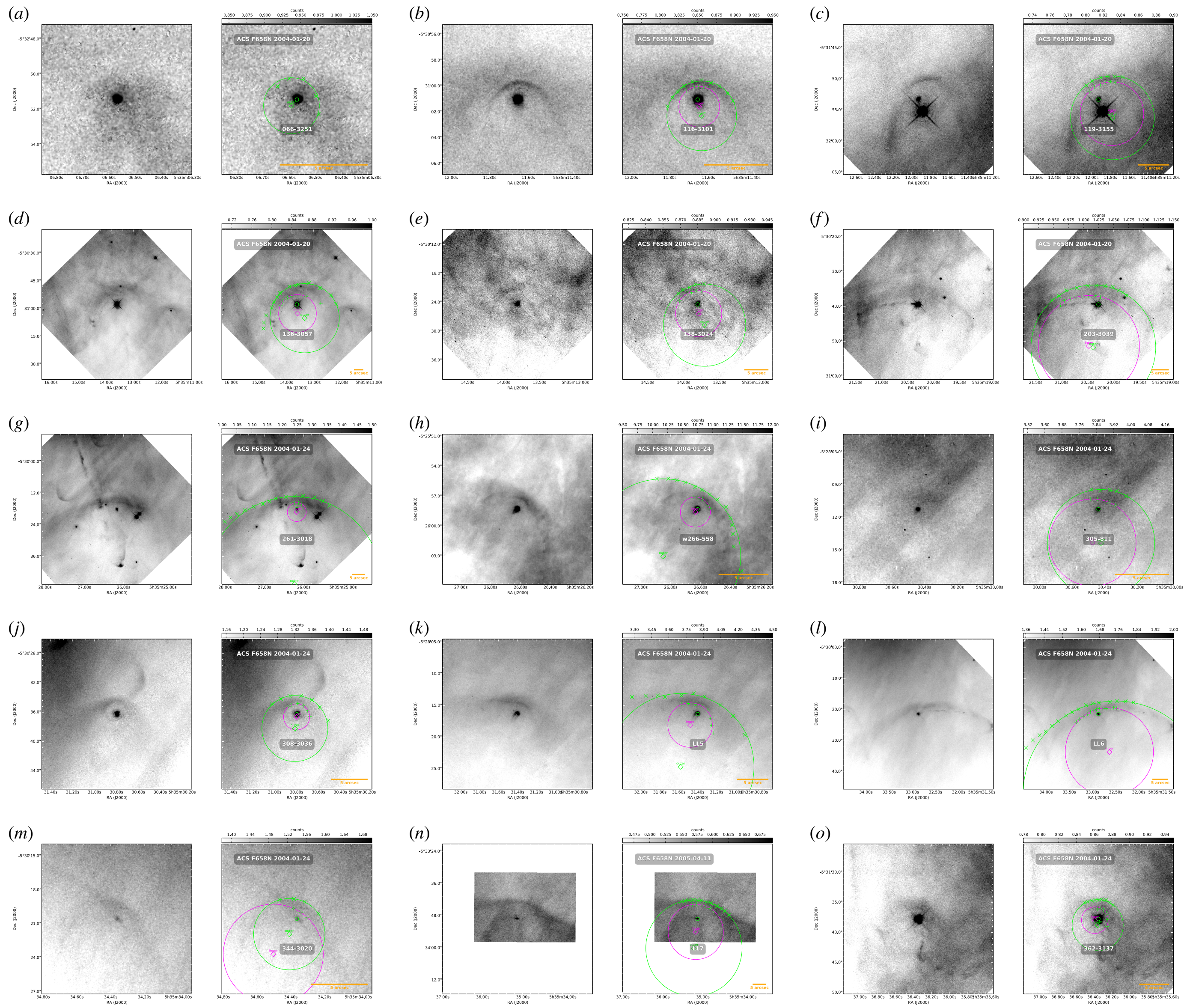

Figure 11. Stationary arc sources in the South group.

northeast. The emission arc wraps around a proplyd, and was designated LLP 315-816 or 314-816. This object has a double-shell morphology with a bright inner rim.

LL 6 (329-3021). (Bally & Reipurth 2001) identified a LL Orionis-type wind-wind collision fronts LL 6 in the outskirts of the Orion Nebula. LL 6 is associated with the star NX Ori, which is surrounded by a large arc of emission (Bally et al. 2006). The wings of the bowshock are very open and extended. This object has a prominent, one-sided jet, oriented perpendicular to the axis of the LL arc. It is difficult to distinguish between the wings of the LL arc and the jet-driven bowshocks.

344-3020. Bally et al. (2006) catalogued a proplyd associated with an emission arc, designated LL 344-3020. This object is very faint and has a bipolar jet at P.A. = $45°$.

LL 7 (351-3349). This object is a LL-type bowshock previously reported by Bally & Reipurth (2001). The central source is a previously catalogued proplyd (Ricci et al. 2008), designated 351-3349. This object has a jet at P.A. $\sim 80°$ perpendicular to LL arc axis. The bowshock wings are very open, and it is one of the most distant emission arcs from the Trapezium in this catalog. This object is larger than we show, the bowshock from jet overlap wings of LL arc (see Bally & Reipurth 2001).

362-3137. This is a previously uncatalogued proplyd associated with an emission arc. However, Da Rio et al. (2009) catalogued the central source as a star. The source is a double star. It is located at north of LL 7. This object seems to show a double-shell morphology. There is a filament to south probably unrelated to the object. This emission arc has not been previously reported in the literature.

3.8. *Interproplyd shells*

The interproplyd shell is a group of small proplyds, which they are associated with small emission arcs which are formed by the interactions between two individual photoevaporation flows.

066-652. This object was previously classified as irregular by O'Dell & Wong (1996). It was cataloged as a proplyd and

Table 10
Shell geometric parameters of interproplyd shells

Object	RA	Dec	D	PA	$R_{\rm out}$	$R_{\rm in}$	$R_{\rm c,out}$	$R_{\rm c,in}$	h	$\rm PA_{out}$	$\rm PA_{in}$
066-652	05:35:06.59	−05:26:52.4	255.85	34.9	0.03	-0.07	0.57	0.60	0.10	316.8	341.9
160-350	05:35:15.96	−05:23:49.7	27.91	13.3	0.11	0.04	0.60	0.29	0.07	226.2	224.3
162-456	05:35:16.18	−05:24:56.4	93.91	1.9	0.29	0.21	0.85	0.79	0.09	28.8	49.2
168-326N	05:35:16.83	−05:23:26.0	7.49	297.4	0.23	0.12	1.04	0.79	0.11	137.0	142.2
173-342	05:35:17.32	−05:23:41.4	23.46	323.5	1.29	0.83	3.31	1.72	0.46	82.2	76.1
175-321	05:35:17.46	−05:23:21.1	16.03	264.7	2.03	1.38	2.48	2.63	0.60	298.7	324.5
204-330	05:35:20.40	−05:23:30.0	60.39	277.1	0.33	0.11	1.34	1.28	0.22	112.4	119.0

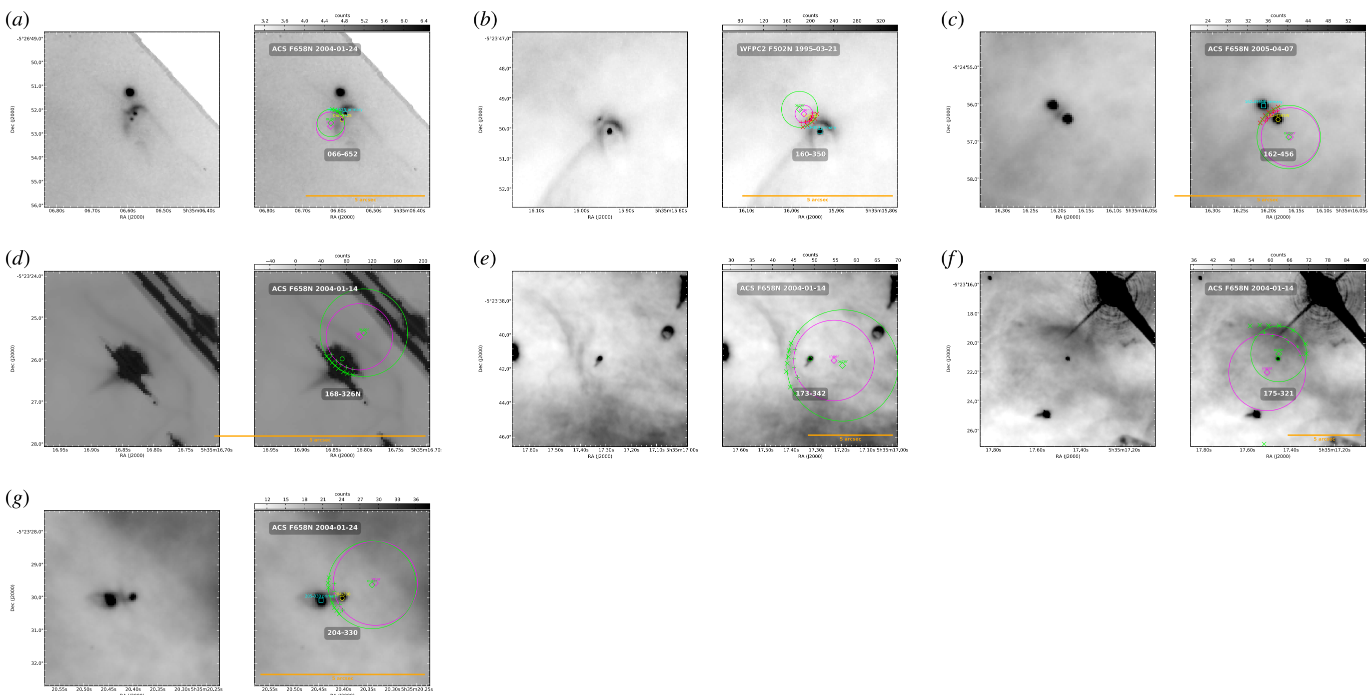

Figure 12. Stationary arc sources in the Interproplyd shells.

binary system by Ricci et al. (2008). An small emission arc is associated with this proplyd.

160-350.

162-456.

168-326N.

173-342.

175-321.

204-330.

3.9. *probably not shells*

131-046.

212-400.

4. DISCUSSION

Proplyd over star fraction falls off relatively smoothly with projected distance. Albeit with a sudden drop after about 200 arcsec.

Bowshock over proplyd fraction seems to have three separate peaks. Very small distances corresponding to the wind-wind interaction, then there is a dearth of bowshocks until a second peak around four arcmin. Finally at very large radii there may be a third peak of objects that are not proplyds.

But an alternate explanation for the third peak could be that they are all proplyds but that the proplyd fraction is underestimated at large distances.

On the other hand there is also evidence for three distinct populations from the azimuthal distribution around the Trapezium. The group at 4 arcmin separation are mainly to the west whereas the more distant objects are mainly to the south.

For clarity, we have omitted many secondary features and slightly increased the size of the smaller features, such as Orion South. The sizes of the smaller features of the different features have been modified slightly

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Table 11
Shell geometric parameters of problematic objects

Object	RA	Dec	D	PA	$R_{\rm out}$	$R_{\rm in}$	$R_{\rm c,out}$	$R_{\rm c,in}$	h	$\mathrm{PA_{out}}$	$\mathrm{PA_{in}}$
131-046	05:35:13.06	−05:20:45.8	164.46	162.4	3.55	1.00	7.33	5.64	2.17	140.3	144.2
212-400	05:35:21.18	−05:24:00.5	80.99	297.9	1.07	0.84	0.83	0.52	0.21	331.2	335.5

(*a*) (*b*)

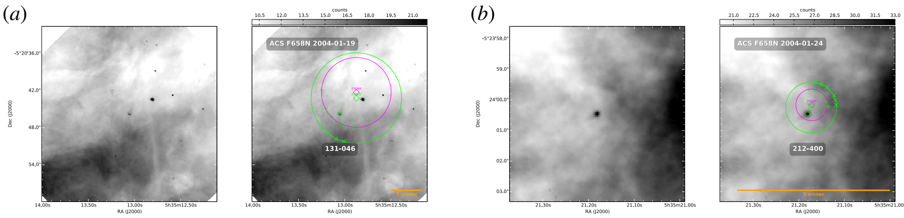
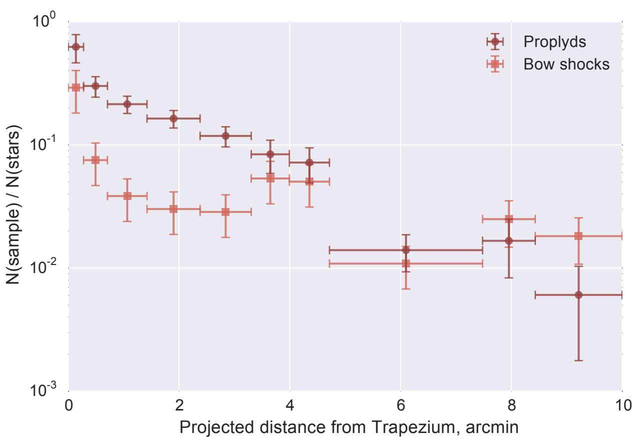


Figure 13. Stationary arc sources in the Problematic objects.

(*a*)



(*b*)

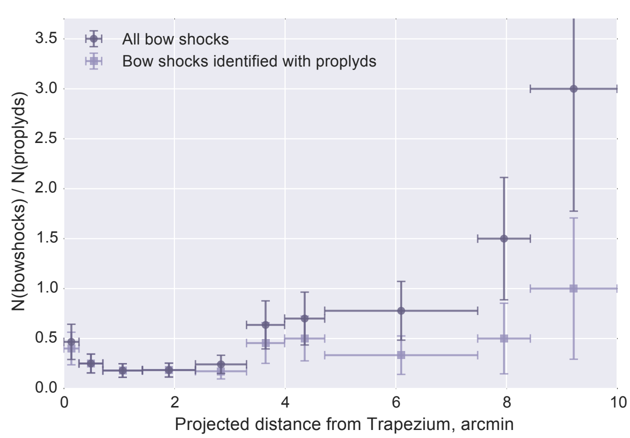


Figure 14. (*a*) Fraction of all optically visible stars that are proplyds (dark circle symbols) or have bowshocks (light square symbols) as a function of projected separation from the Trapezium. (*b*) Ratio between number of bowshocks and number of proplyds as a function of projected separation from the Trapezium. Dark circle symbols show all bowshocks in our catalog (with the exception of interproplyd shocks) while light square symbols show only those bowshocks associated with known or suspected proplyds.

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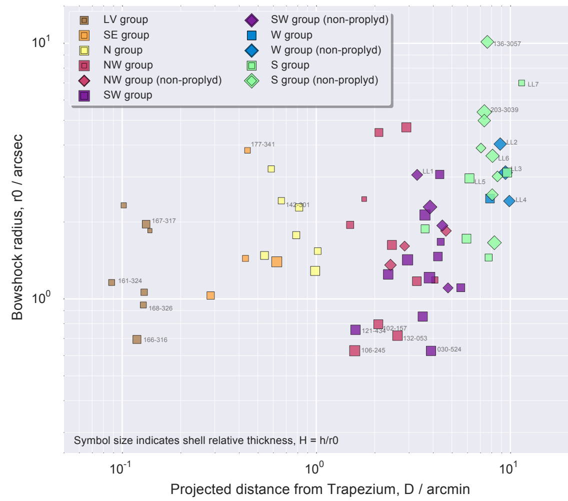

Figure 15. Bowshock axial size versus distance from the Trapezium.

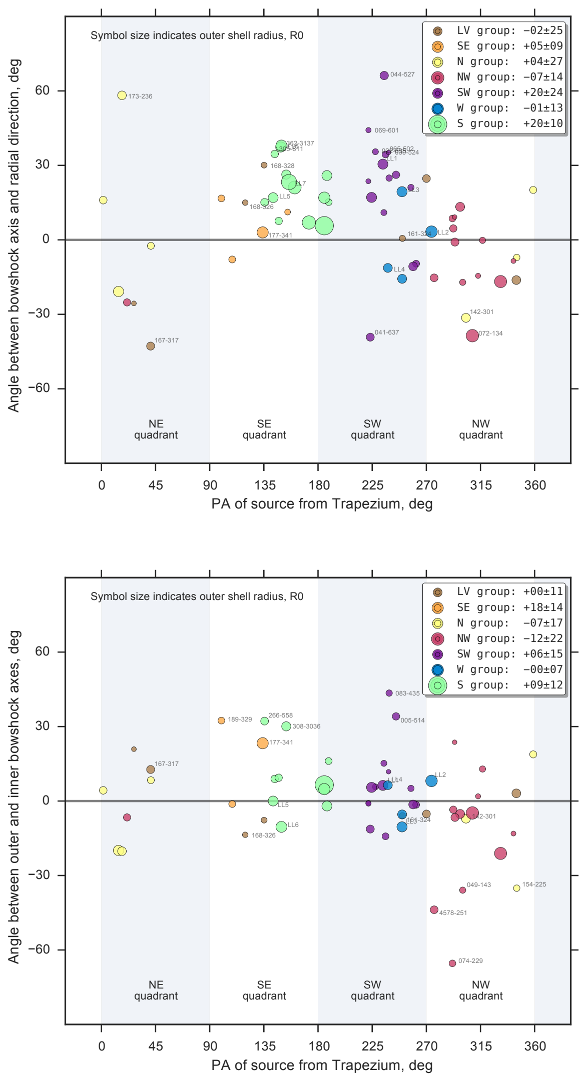

Figure 16. Angle offset between bowshock axis and the radial direction to θ^1 Ori C .

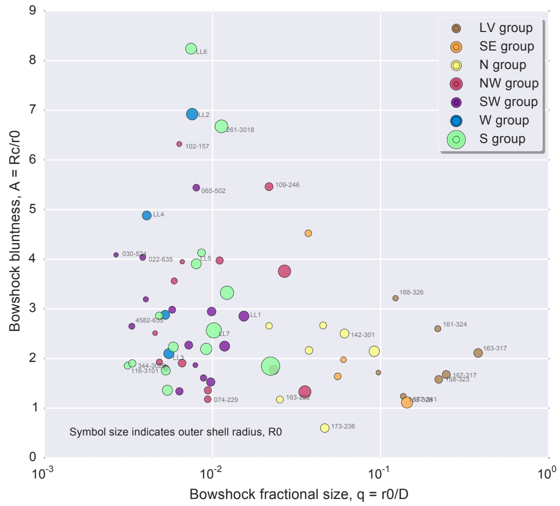

Figure 17. Bowshock bluntness versus relative size.

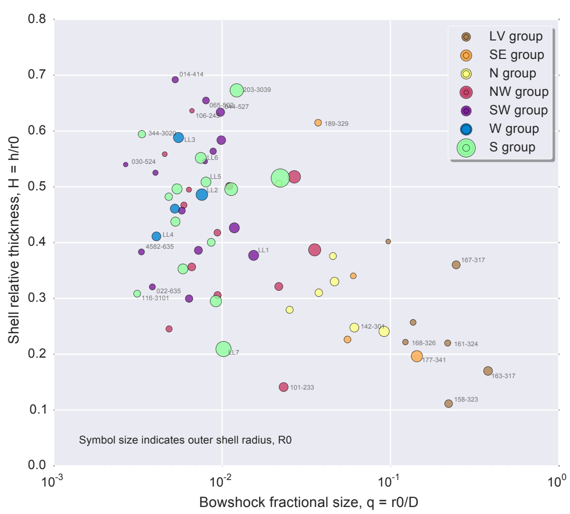

Figure 18. Bowshock relative shell thickness versus relative size.

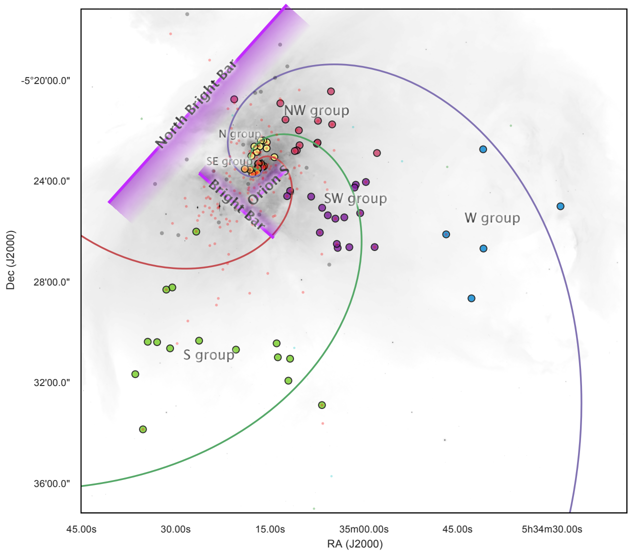

Figure 19. The interlocking spirals.

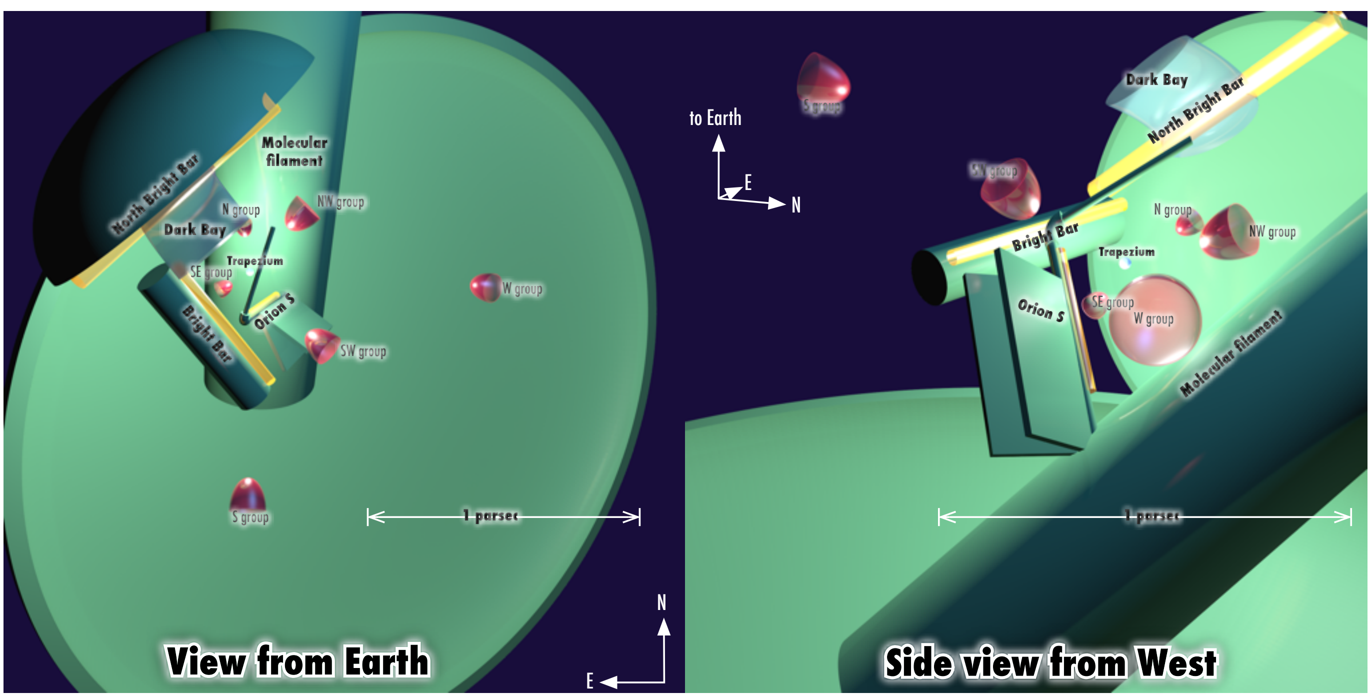

Figure 20. Simplified three-dimensional structure of the Orion Nebula.