ABSTRACT

In the course of a search for common proper motion binaries in the Jones & Walker (JW) catalogue of proper motions in the Orion Nebula Cluster, we came across several faint stars with proper motions larger than one arcsecond per century and probabilities of membership $P$ larger than 0.90. Such stars are interesting because they could be low-mass runaway stars recently accelerated by $n$-body interactions in compact multiple systems. Of particular interest among these stars is JW 451, which has a $P = 0.98$, the largest transverse velocity among all the stars with $P \geq 0.5$ ($69 \pm 38$ km s$^{-1}$), and a proper motion vector which suggests that it was accelerated by the $\theta^1$ Orionis C triple system some 1000 years ago. A closer examination of those JW stars with $\mu > 1''$ century$^{-1}$ revealed that two other stars, JW 349 and JW 355 (with transverse velocities of $38 \pm 9$ and $90 \pm 9$ km s$^{-1}$ respectively), in spite of being listed with $P = 0$ by JW, should also be considered part of the cluster, because these objects are also externally ionized proplyds. In fact, Hillenbrand (1997) assigns to them probabilities of membership of 0.99. Moreover, the proper motion errors of these two stars are relatively small, and so they are good candidates to be runaway stars recently accelerated in the Orion Nebula Cluster.

Subject headings: astrometry — stars: pre-main sequence — stars:kinematics

1. Introduction

It has been known for a long time that a subgroup of O-B stars exhibits large peculiar velocities ($> 30$ km s$^{-1}$). To explain this kinematic anomaly, two theories have been advanced: (1) Zwicky (1957) and Blaauw (1961) proposed that when the massive primary of a close binary explodes as a supernova of type II, the mass ejected is sufficiently large
to release the secondary with a velocity comparable to its orbital velocity. (2) An alternative explanation proposed by Poveda et al. (1967), succeeded in generating large ejection velocities (> 30 km s\(^{-1}\)) by \(n\)-body interactions from multiple stars whose initial conditions led to very close encounters. The close interactions frequently produced pairs of opposite runaways, like AE Auriga and \(\mu\)-Columbae, the prototype of this family of stars (Morgan & Blaauw 1954). For a recent assessment of the two mechanisms for producing runaways, see Hoogerwerf et al. (2001) and references therein.

The classical runaway stars are massive O-B stars, mostly single. However, both of the above mechanisms could also produce low mass high-velocity stars. Is it a case of observational selection that has made the presence of low-mass runaways to be overlooked? In a study of internal motions of trapezium systems (Allen et al., 1974, 2004) we pointed out the existence of some low mass stars that appear to be leaving their host multiple systems with large velocities. Moreover, recent work (Loinard et al., 2003) has revealed the existence of a low-mass star that seems to escape from the T-Tauri system with a space velocity large enough to qualify as a runaway.

As part of a long term investigation on the distribution of separations of wide binaries of different ages (Poveda et al. 2004), two of the present authors (Poveda & Hernández-Alcántara 2003) looked for common proper motion binaries in the Orion Nebula Cluster, taking advantage of the very extensive list of precise proper motions by Jones & Walker (1988, henceforth JW). In the course of this investigation, our attention was attracted by star 451 in the JW catalogue, because its listed proper motion is the largest among all the stars with \(P > 0.5\), and corresponds to a relative transverse velocity of some 69 km s\(^{-1}\) at the adopted distance of the Orion cluster (470 pc). The direction of the velocity vector is such that the star seems to have been ejected from \(\theta^1\) Orionis C. Moreover, Jones & Walker assign to this star a probability of membership of 0.98.

On closer examination, stars JW 349 and JW 355 also turn out to have large transverse velocities (38 km s\(^{-1}\) and 89 km s\(^{-1}\), respectively). Despite having \(P = 0\) in the JW catalogue, Hillenbrand assigns to these stars a probability of membership of 0.99 because they have been recognized as externally ionized proplyds.

In the present letter we briefly discuss the kinematics and the nature of these stars. We examine whether or not they are low-mass runaway stars as well as their probable sites of acceleration; we propose that their kinematic behavior could be the result of dynamical interactions in tight multiple systems.
2. Jones-Walker 349

Among the large (transverse) velocity objects in the JW catalogue we find star 349, with \( \mu_x = (-1.56 \pm 0.21)'' \) century\(^{-1} \) and \( \mu_y = (-0.73 \pm 0.32)'' \) century\(^{-1} \), which corresponds to a transverse velocity of \( 38 \pm 9 \) km s\(^{-1} \) assuming with JW a distance to the Trapezium cluster of 470 pc. The large velocity and the small errors, as well as the fact that it is an externally ionized proplyd (Hillenbrand, 1997), make this object particularly convincing as a runaway star in the Trapezium Cluster.

The method used by JW to determine membership to the cluster involves a sophisticated modeling of the surface densities and motions of both cluster members and field stars. However its application to the Trapezium Cluster is complicated by the fact that there exists an effective absorption sheet that practically obscures all background stars (Hillenbrand, 1997). Since all three stars we are studying are externally ionized proplyds, one can infer that they are indeed members of the cluster, and not projected foreground stars.

In Table I we list the proper motions \( \mu_x, \mu_y \) of this star together with their one \( \sigma \) errors. In Fig. 1, adapted from McCaughrean (2001), the proper motion vectors of this star plus and minus their one \( \sigma \) errors are drawn, along with a few stars in the Orion Trapezium area. The figure suggests that this object was ejected from the Trapezium, either from \( \theta^1C \) or from components \( \theta^1A \) or \( \theta^1B \). If it was ejected from any of these multiple systems, then it was accelerated some 6,000 years ago. Not having a spectral type for this object, it is difficult to estimate its mass and its age. However, given the apparent infrared magnitude \( (I = 12.9) \) listed in JW, and the fact that it is an externally ionized proplyd, we can infer that it is in front of the Orion molecular cloud and embedded in the Orion H II region. Its faint infrared magnitude is probably indicative of a low-mass object. The star appears in JW catalogue as a variable. This is to be expected if it is in fact an extremely young object, still in contraction towards the main sequence.

3. Jones-Walker 355

Star 355 in the JW catalogue is listed with a large proper motion: \( \mu_x = (3.71 \pm 0.33)'' \) century\(^{-1} \), \( \mu_y = (-1.51 \pm 0.24)'' \) century\(^{-1} \), which corresponds to a transverse velocity of \( 89 \pm 9 \) km s\(^{-1} \). It has a JW probability of membership \( P = 0 \). With this probability we should drop this star from consideration. However, we retained it as a member of the cluster because Hillenbrand (1997) lists it as an externally ionized proplyd with a \( P = 0.99 \), and O’Dell & Wong (1996) also lists it as a proplyd. Hence its membership to the Trapezium cluster seems reliable. Unfortunately there are no data available on its spectrum, or photometry, apart
from a JW infrared magnitude of 12.9. The star is listed by JW as variable. The errors of
the proper motion are small, which makes the case for its large velocity quite convincing.

In Table 1 we list values of the proper motions and transverse velocities considering
errors of ±σ. In Fig. 1 we show, superposed on the image of the Orion Nebula Cluster,
the proper motion vector of JW 355, as well as the vectors that result from adding and
subtracting to µx and µy their one σ errors. Projecting to the past the proper motions
shown in Fig. 1, we find no object as conspicuous as θ1 Orionis C. However, searching within
the sector defined by the one σ errors and up to two degrees away (~ 150,000 years back), we
found an interesting object, namely [TUK 93]28 (Tatematsu et al., 1993), a dense molecular
core observed at Nobeyama in the line CS (1-0) at 49 GHz, with an estimated mass of 260
M⊙ and a radius of ~ 30,000 AU. Its line width of 1.65 km s⁻¹ is indicative of the presence
of young stellar objects in the core (Tatematsu et al., 1993). If the core [TUK 93]28 is the
place where JW355 was accelerated some 5,000 years ago, it would be qualitatively similar
to the scenario where the Becklin-Neugebauer object was accelerated 500 years ago in the
Kleinman-Low Complex (Rodriguez et al., 2005). With an apparent magnitude of I = 13.6,
JW 355 is clearly a low-mass star.

4. Jones-Walker 451

This star is listed by JW as having proper motion components: µx = (-3.06 ± 1.49)"/century,
µy = (0.31 ± 0.84)"/century, with an infrared magnitude I = 12.2 and a probability
of membership P = 0.98. In Table 1 we list the various values of the proper motion and
transverse velocities that result when considering the errors, again assuming a distance of
470 parsecs. In Figure 1, the proper motion vector of this star is shown. We also draw the
vectors found when adding and subtracting to µx and µy their one sigma errors (σx, σy). The
proper motion vectors of JW 451 are consistent with the concept that this star was ejected
from θ1 Orionis C about a thousand years ago.

The errors (σx, σy) listed for this object are rather large, which is understandable because
of its non-stellar image (proplyd). In fact, the frequency distribution of the σx and σy for
objects with P > 0.5 in the JW catalogue, has a dispersion which is about three times larger
for the 68 proplyds than for the remaining (non-proplyd) stars.

Even if one assumes for this object the most unfavorable combination of the components
µx and µy with their errors (see vector a in Table 1 and in Fig. 1), JW451 still remains as
a runaway star coming out of the Trapezium. In other words, with the data available, it is
more likely than not that JW451 is a runaway star ejected from the Trapezium. Clearly this
star is interesting enough to deserve further astrometric and radial velocity studies.

**TABLE 1 HERE**

We have searched the literature for information on this star and have found no additional data on its astrometry. We did find some photometric and spectroscopic data. Hillenbrand (1997) describes this object as an externally ionized proplyd, which confirms its membership to the Orion Nebula Cluster and its physical proximity to \( \theta^1 \) Orionis C (see also O’Dell & Wen 1994); moreover, its bolometric luminosity \( (L = 1.3L_\odot) \) and its spectral type (M3e) are consistent with JW 451 being very young. No visual magnitude for this object is available. From the values of the \( V - I \) index for the various M3e stars in Table 1 of Luhman et al. (2000), we adopted a mean \( V - I \simeq 3.3 \) which, when applied to the infrared magnitude, gives an approximate visual magnitude of 15.5.

With the bolometric luminosity, spectral type and temperature from Table 1 of Luhman et al. (2000), the position of JW 451 on the temperature-luminosity diagram for the stars of the Orion Nebula cluster was plotted (see their Fig. 6). They also plotted various gravitational contraction tracks for stars of different masses. From this diagram, one can infer approximate values for the mass and age of JW451. Table II summarizes the best values we have found to characterize this object, with data taken from Hillenbrand (1997), Luhman (2000) and Jones & Walker (1988). The star is also listed by JW as a variable, not surprising in view of its spectral type and its extreme youth.

**TABLE 2 HERE**

5. Discussion and conclusions

The dynamical ejection scenario turns out to be particularly intriguing when we take into account the case of the Becklin-Neugebauer object (BN) which, according to Tan (2004) has a transverse velocity of \( 38.7 \pm 4.7 \) km s\(^{-1}\) and appears to have been ejected again from \( \theta^1 \) Orionis C about 4000 years ago. Where do these objects come from? Three run-away stars ejected from \( \theta^1 \) Orionis C in six thousand years seem unlikely. Therefore we examined recent work on the whole Becklin-Neugebauer Kleinman-Low (BN-KL) complex. A companion paper (Rodríguez et al. 2005) shows convincingly that BN was not ejected from \( \theta^1 \) C but rather from the complex I-IRC\(_2\), probably as the result of \( n \)-body interactions.

Based on the data collected in the previous sections, we propose that JW 349 and JW451 are low-mass runaway stars that were recently ejected from the Orion Trapezium, (see Figure 1). At present, \( \theta^1 \) C appears to be a hierarchical triple system, composed of
a spectroscopic binary with a period of 66 days ($a \approx 1$ AU) and a 10 to 100 year period speckle-resolved companion with a mass $\geq 6M_\odot$ (Schertl et al. 2003; Vitrichenko 2002). If JW349 or 451 were indeed ejected from $\theta^1$ C a few thousand years ago, $\theta^1$ C must have been an unstable multiple system, at least quadruple and itself a sub-trapezium, from which by strong dynamical interactions (given the large mass of $\theta^1$ C) either JW451 or JW349 were ejected with a large velocity. Because of the small mass ratio of either JW349 or 451 to $\theta^1$ C ($\leq 0.01$) the recoil velocity of $\theta^1$ C is lost within its peculiar motion; furthermore, the present binding energy of the system $\theta^1$ Orionis C plus the kinetic energy of either JW349 or JW451 remains strongly negative.

Note that components A and B of the Orion Trapezium are also known to be multiple systems. This is particularly interesting, because high resolution images (Figs. 4, 5 and 6 of Close et al. 2003) show $\theta^1$ B to be a quintuple system, and $\theta^1$ A a triple; in both cases the similarities of the separations of some of the components indicate that they too are dynamically unstable systems. These two components of the Trapezium are, in addition to $\theta^1$ C, good candidates for the site of acceleration of JW349 and JW451; hence, within the uncertainties of the past trajectories of these stars, we find three multiple stars which could have accelerated two young low-mass runaway stars. JW355 most likely was accelerated within the dense molecular core [TUK 93] 28.

These four runaway stars (JW349, 355, 451 and BN) must have been accelerated by the mechanism of $n$-body interactions and not by any supernova explosion, since a few thousand-year old type II supernova remnant in the Trapezium, in the BN-KL region, or in [TUK 93] 28 would exhibit not only wild kinematics but also the presence of very strong non-thermal synchrotron emission, neither of which is observed.

We summarize our conclusions as follows: (1) JW349, 355 and 451 are young, recently accelerated, runaway stars. (2) $\theta^1$ Orionis A, B and C have been strongly interacting dynamically unstable multiple systems, which appear to have produced two runaways in the last few thousand years. (3) We have here four convincing cases (BN, JW349, JW355, and JW 451) for runaway stars being produced by $n$-body interactions, and not by a type II supernova explosion. (4) JW349, 355, 451 are good examples of the existence of low-mass runaway stars. (5) These four runaway stars seem to indicate that the process of star formation involves the frequent acceleration of runaway stars in tight multiple systems.

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Table 1. Kinematic data for JW 349, 355, and 451

| Star   | $\mu_x$ | $\mu_y$ | $|\mu|$ | Vt  |
|--------|---------|---------|---------|-----|
|        | "/century | "/century | "/century | [km s$^{-1}$] |
| JW 349 | a +σ: -1.35 -σ: -1.05 1.71 38 | b -σ: -1.77 -σ: -1.05 2.06 46 | c -1.56 -0.73 1.72 38 | d +σ: -1.35 +σ: -0.41 1.41 31 | e -σ: -1.77 +σ: -0.41 1.82 40 |
| JW 355 | a +σ: 4.04 -σ: -1.75 4.40 98 | b -σ: 3.38 -σ: -1.75 3.81 85 | c 3.71 -1.51 4.01 89 | d +σ: 4.04 +σ: -1.27 4.23 94 | e -σ: 3.38 +σ: -1.27 3.61 80 |
| JW 451 | a +σ: -1.57 -σ: -0.53 1.66 37 | b -σ: -4.55 -σ: -0.53 4.58 102 | c -3.06 .31 3.08 69 | d +σ: -1.57 +σ: 1.15 1.95 43 | e -σ: -4.55 +σ: 1.15 4.69 104 |
Table 2. Parameters for JW451

<table>
<thead>
<tr>
<th>I</th>
<th>V</th>
<th>SP</th>
<th>(T_{\text{eff}})</th>
<th>(L_{\text{Bol}}/L_\odot)</th>
<th>(M/M_\odot)</th>
<th>Age (years)</th>
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<td>12.2</td>
<td>15.5</td>
<td>M3e</td>
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<td>1.3</td>
<td>0.2-0.3</td>
<td>4700</td>
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Fig. 1.— Proper motion vectors of runaway stars JW 349, JW 355, and JW 451 in relation to the Trapezium stars, superposed on an infrared image of the center of the Orion Nebula Cluster, from McCaughrean (2001). Vectors a, b, c, d, e correspond to the various combinations of $\mu$ with their $\sigma_x$, $\sigma_y$ errors. Objects Becklin-Neugebauer (BN) and Compact Radio Source I are also plotted, along with their proper motion vectors (Rodriguez et al. 2005).