The Initial Physical Conditions of the Orion BN/KL Fingers

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Abstract

Orion BN/KL is an example of a poorly understood phenomena in star-forming regions involving the close encounters of young stellar objects. The explosive structure, the variety of molecules observed, the energy involved in the event, and the mass of the region suggest a contribution to the chemical diversity of the local interstellar medium. Nevertheless, the frequency and duration of other, similar events have not been determined. In this paper, we explore a recent analytic model that takes into account the interaction of a clump with its molecular environment. We show that the widespread kinematic ages of the Orion fingers—500 to 4000 yr—are a consequence of the interaction of the explosion debris with the surrounding medium. This model explains satisfactorily the age discrepancy of the Orion fingers, and inferences the initial conditions together with the lifetime of the explosion. Moreover, our model can explain why some CO streamers do not have an associated H₂ finger.

Unified Astronomy Thesaurus concepts: Interstellar medium (847); Interstellar dynamics (839)

1. Introduction

Orion BN/KL is a complex, massive star formation region that is associated with an explosive event that occurred some 500 yr ago. In particular, it contains around 200 filamentary structures in H₂ emission known as the Orion fingers, which could be formed by the close encounters of young stellar objects (Zapata et al. 2009; Bally et al. 2011, and references therein). The most accepted interpretation of these fingers is that they were formed by the interaction of high-velocity gas clumps with the environment (Bally et al. 2017). We will consider this interpretation.

The age of the event has been determined by several authors using different techniques. Bally et al. (2011) analyzed the projected position and velocity of the heads of the H₂ fingers. For each finger, they found an individual age that is between 1000 and 500 yr. This is in contradiction with the idea that Orion BN/KL was produced by a single explosive event and that the expelled clumps are in ballistic motion, so they concluded that there must be some deceleration. Zapata et al. (2009) reported the counterpart of the H₂ fingers, observing the J = 2 → 1 CO transition, called CO streamers. Each streamer has a radial velocity that increases linearly with the distance to a common origin and, assuming a simultaneous event, the authors determined the 3D structure and obtained a most probable age of approximately 500 yr. This is in agreement with the age estimated by Rodríguez et al. (2017), who used the proper motions and projected positions of the runaway objects I, n, and BN to estimate a close encounter 544 yr ago. Also, Zapata et al. (2011a) calculated the age of an expanding bubble in CO centered in the same possible origin of the region. The radial velocity and the size of this outflow result in ~600 yr. The momentum and kinetic energy of this outflow are at least $160 M_\odot$ km s$^{-1}$ and $4 \times 10^{46}$ erg (Snell et al. 1984) or $4 \times 10^{47}$ erg (Doi et al. 2002).

There is a chance that the fingers could have originated at different times. Perhaps there is an unexplored mechanism that would produce such an extended structure. The machine-gun model has been mentioned as a possible explanation, but previous models (Raga & Biro 1993), even when they are not collimated, are far from being as isotropic as the Orion fingers. Runaway stars (Rodríguez et al. 2017), the expansion of the molecular bubble (Zapata et al. 2011b), and the age determined by the CO streamers (Zapata et al. 2009) are strong evidence of a single and simultaneous event. Thus the widespread ages could be explained by a dynamical model that takes into account the deceleration of a dense clump by the surrounding environment.

There have been several attempts to describe the interaction of a moving cloud against a static medium. De Young & Axford (1967; hereafter DA) analyzed the plasmon problem, which consists of a moving cloud that adopts a particular density structure, and derived its equation of motion. Cantó et al. (1998) improved the plasmon solution by including centrifugal pressure. Raga et al. (1998) proposed an equation of motion of a static spherical cloud accelerated by a high-velocity wind due to ram pressure. More recently, Rivera-Ortiz et al. (2019; hereafter RO19) proposed a modification to the plasmon problem, considering the mass lost by the clump, which can modify the plasmon dynamic history if it is embedded in a high-density environment. The plasmon problem is based on the direct consideration of the balance between the ram pressure of the environment and the internal stratified pressure of the decelerating clump. Figure 1 represents the plasmon profile adopted by the pressure balance, the post-shock region, where the material is ionized, and the inner neutral region. A similar representation has been proposed by Burton (1997).

Thus dynamical analysis of the motion of the Orion fingers could lead to a better understanding of the conditions that formed such a structure. Bally et al. (2015) performed numerical simulations of the fingers using observational restraints and obtained a notable resemblance to the actual fingers. Nevertheless, as they described, the interpretation of such simulations is limited since they used an adiabatic system while, in reality, the cooling length is much shorter than the total length of the longest fingers. Therefore, more detailed numerical solutions and an adequate analytic model can be helpful in determining the physical conditions and, perhaps, the ejection mechanism of the fingers, which can aid the...
Environment has density deforms the initial clump, which becomes a plasmon in a negligible time. The conclusions in Section 4. Properties for the clumps before the explosive event that analyzed; in Section 3 we present the estimation of the and the motion direction.

A schematic representation of the initial clump at the moment of ejection. The ejected clump takes a plasmon profile by the pressure balance between the internal pressure and the ram pressure produced by the velocity component $v \cos \alpha$, where $\alpha$ is the angle between the plasmon surface normal and the motion direction. (b) In our model (see RO19) the reverse shock deforms the initial clump, which becomes a plasmon in a negligible time. The environment has density $\rho_x$ and the plasmon has velocity $v$ and density $\rho(x)$ with a density structure studied in DA. The post-shock region that separates the environment and the plasmon structure has been exaggerated for clarity. An intermediate phase between these two cases was closely studied by Burton (1997) and Bally et al. (2015).

Understanding the relevance and duration of similar events in the star-forming processes.

Adopting an age of $t = 544$ yr (Rodríguez et al. 2017), we propose a model to obtain the physical conditions of the ejection. The mass-loss plasmon has a implicit dependence on its own size and this can be used to find better restrictions on the ejection mechanism.

In Section 2 we describe the sample of objects to be analyzed; in Section 3 we present the estimation of the properties for the clumps before the explosive event that generated the fingers in Orion BN/KL. We summarize our conclusions in Section 4.

2. Obtaining the Physical Parameters of the Fingers

2.1. Proper Motions

From Lee & Burton (2000), Doi et al. (2002), and Bally et al. (2011) we have obtained the proper motion of several features and the projected positions for the reported data. In the following paragraphs we describe with more detail how this was done.

1. Lee & Burton (2000) analyzed the proper motions of 27 bullets, with emission in [Fe II], and 11 H$_2$ knots, using a time baseline of 4.2 yr (see Figure 2). From these 38 objects only 19 have proper motion vectors aligned with the position vectors with respect to IRc2, the possible origin of the explosive event. They used a distance to the Orion Nebula of $d = 450$ pc (Genzel & Stutzki 2002), which is larger than the actually accepted $d = 414$ pc (Menten et al. 2007), and leads to an overestimation of the projected distance and proper motion of the data. We have corrected this effect for this paper. In general, they conclude that the farther features have larger proper motions, which is consistent with, at least, some kind of impulse with an age shorter than 1000 yr. However, it is interesting to note that they reported some H$_2$ knots as almost stationary, but these are not included in the final analysis.

2. Doi et al. (2002) measured the proper motions of several Herbig-Haro (HH) objects in the Orion Nebula. For the Orion BN/KL region they found 21 HH objects moving away from IRc2. Like Lee & Burton (2000), they found that the larger objects are faster. HH 210 is also a prominent feature that has a proper motion of almost $400 \text{ km s}^{-1}$. The uncertainties led them to fit an age of $1010 \pm 140$ yr. Even in this case, several objects are not in the range of $870–1150$ yr. Also, they used a distance of 450 pc, which has been corrected in this work to 414 pc.

3. Bally et al. (2011; see also Cunningham 2006) obtained the proper motions of 173 fingers in H$_2$, but in this case there is no clear evidence for a linear dependence of the velocity on the projected distance. They only mentioned
that the age of the event could be between 500 and 1000 yr, depending on whether the simultaneous ejection assumption is maintained. The three data sets are represented in Figure 2.

4. Zapata et al. (2009) analyzed the CO streamers that seem to be related to the fingers. These streamers are around two times shorter and narrower than the fingers and each one follows a Hubble law. The kinematic age of each could be related to the projection angle with respect to the plane of the sky and, assuming that the explosion was isotropic, they found that the most probable age is around 500 yr. Bally et al. (2017), using ALMA, found more streamers and confirmed that these have isotropic extension. This means that some of the CO streamers do not have associated fingers.

2.2. Mass, Density, and Size

From Rodríguez et al. (2017), Cunningham (2006), and Bally et al. (2017) we have obtained the mass, density, and size of several features and the projected positions for the reported data. In the following paragraphs we also describe with more detail how this was done.

1. Recently, Rodríguez et al. (2017) has measured, with high precision, the proper motions of the objects I, BN, and n. They found that these objects had to be ejected from a common origin 544 ± 6 yr ago. This uncertainty does not take into account systematic effects, which can increase it up to ±25 yr. In any case, 544 yr is consistent with the age of 550 yr determined by the CO streamers. In this work, we assume this event to be the origin of the ejection of the material that created the fingers and the streamers.

2. Cunningham (2006) measured 8M⊙ as the mass of the moving gas. We can use this estimate to find the upper limits for either the mass of an individual clump or its size. Nevertheless, due to the complexity of the region there is an uncertainty of factor two in this mass estimate.

3. For the mass, we assume that the observed moving gas corresponds exclusively to that of the ejected clumps. Since there are 200 fingers, then the average mass of each clump is simply 8/200 = 0.04M⊙. An inferior limit for the clump mass is that calculated by Allen & Burton (1993) and Burton & Allen (1994) of 10−5M⊙ based on the [Fe II] 1.64 μm line flux and size.

4. On the other hand, an upper limit for the size of the initial clump is obtained by adopting the opposite assumption, that is, that all the moving mass comes from the swept-up environmental material and a negligible amount from the clumps themselves. To follow this idea we have to fix the density of the environment. Extinction observations of the region by Oh et al. (2016) and Bally et al. (2017) indicate densities between 103 and 107 cm−3. We adopt this latter limit, na = 106 cm−3. In reality, the density is highly structured (Bally et al. 1987; Kong et al. 2018). A better approximation would be to assume cylindrical symmetry for the integral spine filament with a steep density gradient orthogonal to the spine. In this paper we assume a homogeneous environment; a cylindrical density profile would require us to improve the presented plasmon dynamics.

3. Analytic Model

We now model a finger as a cylinder of radius Ra and individual length li. Thus, the mass swept up by all the fingers (assuming the same radius) is

\[ M_i = \pi R_a^2 \rho d_n a \sum_i l_i. \]  

(1)

where \( \mu = 2 \) is the mean molecular mass, \( m_d \) is the mass of hydrogen, and \( n_a \) is the numerical density of the ambient medium. Considering, as a limit, that \( M_i = 8M_\odot \) is equal to the accelerated mass we can obtain \( R_{cl} \sim 90 \) au; then this is the upper limit for the initial size of the ejected clumps.

3.1. Ballistic Motion

The simplest model is to suppose that every ejected clump travels with constant velocity; therefore, the motion is described by

\[ r = vt. \]  

(2)

Since the projected length \( r \) and the velocity \( v \), also in projection, are observational data, then the age of each clump can be obtained straightforwardly:

\[ t = \frac{r}{v}, \]  

(3)

which is independent of projection.

Therefore each clump has an individual age and if we assume that all of them were ejected in a single event, the ages should be at least similar. This is far from which we observe. In Figure 3 we show the result of Equation (3) applied to the data. The calculation of the spread of the error for the age was done using the standard procedure. The reported errors in the velocities are 10 km s−1 for all the HH objects (Doi et al. 2002), 25 km s−1 for all the H2 fingers (Cunningham 2006), and for the [Fe II] bullets they are reported in Lee & Burton (2000). Then, Figure 3 implies that there was no simultaneous event and that the ballistic motion model is not an appropriate assumption. Deceleration is the most likely interpretation.

Notice that the plasmon model assumes an early interaction of the original clump with the environment that will modify its initial characteristics quickly (shape, density stratification, or sound speed) to those of a plasmon. But the ram pressure prevents the plasmon’s free expansion, and this effect gives shape to the material (see also RO19 and Figure 1).

3.2. Dynamic Model

In order to determine the fundamental parameters that control the dynamics of a high-velocity clump, such as the ejection velocity \( v_0 \), the initial size of the clump \( R_{cl} \), the density of the ejected material \( \rho_{cl} \), and the density of the environment \( \rho_{env} \), or their initial density contrast \( \beta = \sqrt{\rho_{cl}/\rho_{env}} \), we use an analysis based on the plasmon proposed by DA. Assuming a spherical clump at the ejection, the initial mass can be expressed as

\[ M_0 = \frac{4\pi R_{cl}^3 \rho_{cl}}{3} = \frac{4\pi R_{cl}^3 \rho_{env}}{3\beta^2}. \]  

(4)

We assume that every clump was ejected with the same size \( (R_{cl} = 90 \) au) and the environment density is \( 10^7 \) cm−3, therefore we can estimate the ejection conditions. The plasmon
In this section we explore a model that takes into account the deceleration of the clump as it loses mass due to the interaction with the environment. This is the model developed in RO19. As stated in that work, no matter the physical characteristics of the original clump (shape, size, density, velocity, or temperature) the initial interaction of the clump with the surroundings will transform it into a plasmon as proposed by DA. Cantó et al. (1998), and RO19. Mass, on the other hand, is preserved.

RO19 show that the mass $M$, velocity $v$, and position $R$ of the newly created plasmon after a time $t$ of ejection/formation are given by the parametric form

$$ M = M_0 e^{-\alpha (1 - \frac{v}{v_0})}, $$

$$ t = t_0 \int_{v_0/v}^{v} u^{-2/3} e^{-2/3 (1 - u)} du, $$

and

$$ R = v_0 t_0 \int_{v_0/v}^{v} u^{1/3} e^{-2/3 (1 - u)} du, $$

respectively, where $M_0$ is the initial mass of the clump, $v_0$ is the ejection velocity, $u = v/v_0$ is a dimensionless velocity, and $\alpha$ is a parameter given by

$$ \alpha = \frac{8 \lambda}{\pi} + 2 \sqrt{\frac{2}{\gamma - 1}} \left( \frac{1}{\beta} \right), $$

and a scale time $t_0$

$$ t_0 = \frac{R_{cl}}{\beta^2 \left( \frac{16 \pi}{3 \xi_{DA} (\gamma - 1)^2} \right)^{1/3} \frac{1}{v_0}}. $$

Combining Equations (8) and (9), we obtain

$$ \left[ \frac{v_0}{\text{km s}^{-1}} \right] \left[ \frac{t_0}{\text{yr}} \right] = 233 \left[ \frac{R_{cl}}{\text{au}} \right] \alpha^2. $$

The purpose of the present paper is to use Equations (4)–(10) to estimate the physical parameters, such as mass, ejection velocity, and density, of each of the original clumps that produce the fingers we see today and were formed by the interaction of the clumps with the surrounding molecular cloud.

We begin by assuming that all the clumps were ejected in a single explosive event that took place 544 yr ago from the place of the closest interaction that expelled the BN, n, and l objects reported by Rodríguez et al. (2017). So, in Equation (6) we set $t = 544$ yr for all the clumps, although each clump had its own initial mass and ejection velocity.

Next, for each clump we know, from observations, its distance to the origin of the explosion $R$ and its current velocity $v$. Both quantities are those on the plane of the sky. However, we take them as estimates of the real values, since there is no way to de-project them without making further assumptions.

Even so, we need to make a further assumption, since we have more unknowns than equations. We might, for instance, choose to assume a fixed value of $\beta$, which means the same initial density for each clump or, perhaps, the same initial mass, or any other reasonable constraint. We choose, however, to assume a unique initial radius for all the clumps of $R_{cl} = 90$ au, based on the assumption that all the clumps were produced by the close encounter of two protostellar objects that ripped off material with the same cross-section interaction.

Then, we have a set of equations (Equations (5), (6), and (10)) that can be solved for $v_0$, $t_0$, and $\alpha$ simultaneously, and by Equation (4) we also can obtain the mass of each ejected clump. The number density of the surroundings was taken as $n_g = 10^3$ cm$^{-3}$. In Figure 4 we show the trajectories of clumps in the $v$–$R$ plane as calculated by our model, using Equations (5)–(10). A fixed clump radius $R_{cl} = 90$ au was assumed in all the calculations. In the upper panel, we have taken a fixed initial velocity for a clump with $v_0 = 500$ km s$^{-1}$, and varied its initial mass from $2 \times 10^{-2}$ (the lower dashed line) to $2 \times 10^{-3} M_{\odot}$ (the upper dashed line). The solid line marks the time $t = 500$ yr after ejection. In the bottom panel, the initial clump mass is also fixed at $M_0 = 0.2 M_{\odot}$ and each dashed line corresponds to a different initial velocity $v_0$, from 100 to 1100 km s$^{-1}$. The solid line again marks the time $t = 500$ yr after ejection. Note that clumps stop at the same distance, in this case at 75,000 au.

In Figure 5, we can see that the model curves that envelope the data set do not have high-mass ($>0.2 M_{\odot}$) or high-velocity clumps ($>800$ km s$^{-1}$). We could expect slow points with low velocities at a distance greater than $8 \times 10^4$ au, but there is no evidence of such clumps; however, in this case we have that 800 km s$^{-1}$ is the fastest velocity that meets the longer features. Also, a plasmon with ejected mass of 0.2 $M_{\odot}$ will reach a final distance of $\sim 8 \times 10^4$ au. This means that a less-massive plasmon, ejected at less than 800 km s$^{-1}$ could be near to the end of its lifetime or maybe it has already stopped. This could explain the CO streamers that are not related to any H$_2$ finger.

Finally, the RO19 plasmon solution is applied to each object of the data sets of Section 2.1 and the initial mass, ejection density is not constant because of the enlargement of the traveled distance and the mass detachment included in the model.
velocity, and lifetime are obtained and shown in Figures 6, 7, and 8, respectively. The total mass, Figure 6, is 11.93 $M_\odot$ with a mean mass of 0.06 $M_\odot$, which is close to the limits of $4 \times 10^{-2} M_\odot$ analyzed in Section 2.1.

Figure 7 shows the ejection velocity distribution. It is interesting to note that there are two peaks in this distribution around 200 and 500 km s$^{-1}$. Further analysis is required to propose a mechanism of explosion that could explain this characteristic. Also, the total kinetic energy of the model is $3 \times 10^{49}$ erg.
Once the ejection parameters are obtained, we can infer the lifetime and stopping distance of each clump using $v = 0$ in Equations (6) and (7). In Figure 9 we show the distribution of the lifetime for the clumps. This can give an idea of the lifetime of the explosive event; in this case 2000 yr after the explosion, there will be just a few fingers and this may be the reason why there are just a few cases of encounters of this kind.

Finally, in Figure 10 we show the time and position of each clump compared with its own lifetime and stopping distance, respectively. Again, there is a tendency for the most of the clumps to be at the end of their lifetimes. This suggests that some fingers have already terminated, explaining why there are H$_2$ features with no proper motion and CO streamers with no associated H$_2$ fingers. This characteristic can be explained in terms of extinction, but the radial velocities of the H$_2$ fingers
are needed in order to correctly associate them to the CO streamers.

4. Conclusions

The plasmon model is a useful tool for the analysis of the dynamics of a clump interacting with a dense environment. Using the dynamic models presented in DA and RO19 we estimate the physical features, initial velocities, and masses for the components (clumps, [Fe II], and HH objects) reported in Lee & Burton (2000), Doi et al. (2002), and Cunningham (2006).

We obtain that the individual maximum mass for the clumps is $0.2 \, M_\odot$, but the maximum velocity of this sample is $800 \, \text{km} \, \text{s}^{-1}$. The total kinetic energy in this case is $\sim 3 \times 10^{49} \, \text{erg}$, which represents $10^7$ times more energy than that obtained for the total luminosity in the Orion fingers region.

Two other consequences of the plasmon model is that larger ejection velocities produce shorter lifetimes, and the initial mass of a clump determines its stopping distance. The RO19 plasmon model predicts that the longest fingers in Orion BN/KL have almost reached the end of their lifetime, but they are not far from their final length and ejection velocities as high as $800 \, \text{km} \, \text{s}^{-1}$ are required to reproduce the observations. This implies that the slower fingers could have lifetimes as long as 3000 yr, and the explosion signatures could disappear in 2000 yr. The mass-loss plasmon can explain why there are no observable longer fingers because, if clumps were thrown with higher speed or less mass, they would have died by now. Also, the required ejection velocities for most of the longest fingers are about $500 \, \text{km} \, \text{s}^{-1}$ which is less than twice their observed velocity.

Therefore, using the RO19 model we obtained the initial masses of each of the clumps; from their mass distribution we observed that a large number of clumps have a mass in the interval of $8 \times 10^{-3} - 2 \times 10^{-1} \, M_\odot$ and, from the velocity distribution, we obtained a distribution of two populations, one with a maximum at $200 \, \text{km} \, \text{s}^{-1}$ and another with a velocity of $500 \, \text{km} \, \text{s}^{-1}$.

Finally, from our calculated time and position of each clump and its own expected lifetime we can see a tendency for the most of the clumps to be at the end of their lifetimes. We proposed that some fingers have already terminated, which explains why there are $\text{H}_2$ features with no proper motion and CO streamers with no associated $\text{H}_2$ fingers.

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