Supernovae in Orion: The Missing Link in the Star-forming History of the Region

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Abstract

The Orion Complex is a notable star-forming region fragmented into several different populations with substantial differences in their phase space. I propose a model that attempts to explain how the Complex has evolved into this current configuration. In the model presented here, the large-scale expansion can be attributable to a supernova that exploded 6 Myr ago. The remnants of this explosion can be seen as Barnard’s loop, which as the center of the expansion is consistent with the geometrical center of the H II bubble. This is similar to the H II bubble and the ballistic expansion that is associated with λ Ori, a region that was also the site of an ancient supernova. Assuming that the Orion Complex originally formed as one long filament spanning from the bottom of Orion A to σ Ori (or potentially as far as λ Ori), Barnard’s loop supernova could have split the cloud, which led to the formation of Orion C & D. Furthermore, the shockwave that propagated into the filament could have swept along the gas through several parsecs, which led to the formation of the singularly most massive cluster in the solar neighborhood, the Orion Nebula Cluster. I also discuss other related nearby events, such as the formation of the Monogem ring and various runaways that have been ejected from the Orion Complex.

Unified Astronomy Thesaurus concepts: Supernova remnants (1667); Stellar feedback (1602); Young star clusters (1833); Runaway stars (1417); H II regions (694); Star formation (1569); Stellar populations (1622)

Supporting material: Interactive Figure

1. Introduction

The Orion Complex is the closest star-forming region capable of forming a large number of massive stars. Containing more than 10,000 stars that can be associated with the region (Kounkel & Covey 2019), the Orion Complex has influenced much of our understanding of how young clustered populations form and evolve.

In recent years, the release of Gaia DR2 (Gaia Collaboration et al. 2018) has significantly improved the precision of available measurements of the distance and proper motions. Combined with the large number of stars observed with the APO Galactic Evolution Experiment (APOGEE) to obtain high-resolution spectra (and thus precise radial velocities), Gaia DR2 has yielded improved constrains on the 3D structure and 3D kinematics of the Orion Complex (Kounkel et al. 2018, hereafter Paper I). A number of other studies have been conducted with Gaia in Orion, such as, e.g., examining the structure and dynamics of the individual subpopulations (Großschedl et al. 2018; Getman et al. 2019); expanding the census of the members (Chen et al. 2019; Jerabkova et al. 2019b); and searching for kinematically peculiar stars (McBride & Kounkel 2019; Farias et al. 2020; Schoettler et al. 2020).

In addition to Orion A and B molecular clouds—the regions of the current epoch of star formation—the Orion Complex consists of a number of populations that have little molecular gas remaining. Population centered on the λ Ori, located at the head of Orion, is one such population. Others include Orion C & D populations, which are projected on top of one another in the plane of the sky, and they have very similar proper motions; however, they are separated by ~50 pc, and have a ~10 km s^{-1} difference in the radial velocity of the two populations. Orion C contains the σ Ori cluster, and Orion D roughly coincides with the Orion OB1a and Orion OB1b subassociations, although both extend much further than has been generally assumed prior to the release of Gaia DR2 (Paper I).

While all of these populations are kinematically and spatially distinct, they significantly overlap in the phase space, are more alike than they are different, and have comparable ages. Although the structure of the Orion star-forming region is among the most complex in comparison with all of the star-forming regions in the solar neighborhood (Kounkel & Covey 2019), it is difficult to imagine an scenario in which all of the individual subpopulations do not share a common origin. Nonetheless, a question arises: what led to such a peculiar morphology of the Complex? Did it form in this segmented manner in situ, or was there an event that fragmented it?

In this paper, I propose a model that unifies the star-forming history of the Orion Complex that assumes a massive supernova explosion shaped much of its structure and dynamics. In Section 2 I review a case study of λ Ori supernova. In Section 3 I present evidence that of the supernova that is associated with Barnard’s loop, for which λ Ori supernova can be thought as a scale model. In Section 4 I highlight the Monogem ring, which is either a supernova remnant associated with a runaway from the Orion Complex or a signature of bipolar outflow from Barnard’s loop supernova. Finally, in Section 5 I discuss the model of the star-forming history of the Complex.

2. λ Ori

Paper I noted that the λ Ori cluster has a peculiar kinematic signature. While cluster itself appears to be virialized within, outside of 15°, the proper motions of the stars are pointed away from the cluster center. Moreover, the motion is ballistic: the further away they are, the faster they appear to be, up to the speeds of 6 km s^{-1} in the rest velocity of the cluster, and they
proper motions approximate locations of the supernova eruptions. Orion, courtesy of Rogelio Bernal Andreo. The two star makers show the "Figure 1."

the Orion Complex from Kounkel & Covey (2019), color coded by the distance of the stars, from purple at 300 pc to red at 450 pc. Proper motions (pointed from the thicker part of the arrow at the current position, moving toward the thin part) are in the LSR, in the reference frame of the Orion Nebula. Vectors are overlaid on the photograph of Orion, courtesy of Rogelio Bernal Andreo. The two star makers show the approximate locations of the supernova eruptions.

can all be deprojected back toward the cluster center at the age of ~4.8 Myr ago (assuming no acceleration).

λ Ori has long since been theorized to be a site of an ancient supernova explosion that went off several million years ago (Dolan & Mathieu 1999, 2002; Mathieu 2008). That supernova produced an ionized H II bubble. All of the stars associated with this region are firmly enclosed within the bubble (Figure 1). Furthermore, the stars located further toward the edges are younger (~2 Myr) than those found in the cluster center (~5 Myr).

Paper I suggested that the ballistic expansion of stars can therefore be thought of a signature of a supernova. The shockwave has rapidly expunched the molecular gas from the cluster, sweeping it along on the radial trajectory. The stars that have subsequently formed from that molecular gas, as it clumped together, maintained the same trajectory. The gravitational feedback of rapidly dispersing gas may have also contributed somewhat in accelerating the stars (Zamora-Avilés et al. 2019). Although it can be argued what role the shockwave may have had in triggering the subsequent epoch of star formation of the younger population or if those stars have formed regardless of any outside influences (Dale et al. 2015), the net result remains the same. While most young clusters tend to expand somewhat, the typical expansion speeds are on the order of ~0.5 km s⁻¹ (Kuhn et al. 2019). In simulations, formation of stars that have been triggered from photoionization due to radiative feedback can impart velocities to a few stars ~1–2 times higher than the natural velocity dispersion of the cloud, but the overall effect is often difficult to measure (Dale et al. 2015). Acceleration of stars to speeds an order of magnitude higher than requires an outside influence, most likely attributable to the supernova in some form. And, indeed, the expansion of the shocked gas that is observed around recent supernovae (~13 km s⁻¹, Sashida et al. 2013) is sufficient to accelerate the gas, and, subsequently, stars, to the necessary speed.

3. Barnard’s Loop Supernova

In addition to the H II bubble associated with λ Ori, there is another very notable bubble: Barnard’s loop. Its origins are unknown, but it has been theorized that it may have been a byproduct of a supernova (Madsen et al. 2006; Ochsendorf et al. 2015) or that it has been driven by the radiation pressure of the OB stars (O’dell et al. 1967; O’Dell et al. 2011). Similarly, there has been debate whether Barnard’s loop is just a part of the Orion–Eridanus superbubble (Wilson et al. 2005) or whether it is an independent entity (Ochsendorf et al. 2015).

Taken as a whole, much of the Orion Complex is perfectly encircled by Barnard’s loop: from Rigel to ψ² Ori, from the top of Orion B to the bottom of Orion A, not dissimilar to the λ Ori bubble. As such, it is highly likely that they are associated with one another. The geometrical center of the bubble lies approximately a degree away to the southwest of η Ori.

In Paper I we noted that Orion D appears to be expanding, attributing it to a natural evolution due to the age of the population. However, considering that young populations of similar mass can survive as comoving groups for several hundred megayears (Kounkel & Covey 2019), a 8 Myr population tearing itself apart in such a manner appears to be unusual. Upon closer examination, I found that when all of the proper motions for the entire Orion Complex are placed in the common reference frame, the center of the expansion appears to correspond to the geometrical center of Barnard’s loop (Figure 2), and that many of the stars that are moving radially away from it can be traced back to this origin ~6 Myr ago.

Currently, Orion C and Orion D exist as separate entities located at two very different distances of 412 pc and 350 pc respectively, on average. They are colocalized along the recently discovered bubble of dust (Rezaei et al. 2020). However, as Orion C has a radial velocity of ~13 km s⁻¹, and Orion D has a radial velocity of ~4 km s⁻¹ (in the local standard of rest (LSR) reference frame), they are receding away from each other; in the past, they would have been much closer together. They would have been colocalized ~6–7 Myr ago at the distance of ~320–330 pc, not dissimilar to the distance the Orion Nebula Cluster (ONC) would have had at the time (projecting back the current distance of 389 pc with the characteristic RV of 10 km s⁻¹), ignoring the relative motion of the Sun to the LSR. Similarly, prior to the expansion, their average rest-frame radial velocity would have been similar to that of the ONC as well (~8 km s⁻¹). The timescale of the expansion along the

Figure 1,
line of sight is well matched to the expansion in the plane of the sky.

Großschedl et al. (2018) noted that the Orion A molecular cloud has a peculiar shape; that the ONC, the “head” of the cloud, is tilted relative to it; and it is as if pushed by some force perpendicular to the filament. They proposed that it could be attributable to either cloud–cloud collision or due to stellar radiative and supernova feedback. Getman et al. (2019) have also suggested that the compression shock from a feedback from an OB stars from Orion D could be responsible for the dynamical evolution of the head, and that this compression then assisted in the global gravitational collapse of the cloud.

The direction of the compression of Orion A (based on the 3D map, Figure 2) is consistent with originating from the center of the bubble.

In Paper I, we performed hierarchical clustering of the Orion Complex to separate it into ~200 groups that trace the full extent of the Complex, each one representative of the position and velocity of the stars in a particular subregion. These groups can act as tracers of the dynamical evolution of the Complex.

Figure 2. Three-dimensional distribution of the groups in Orion from Paper I. The groups are color coded by the average age of the stars within them, with red being the youngest; the size of the dot corresponds to the number of stars inside each group. The panels show the traceback and the trace forward look over the −8 and +8 Myr, with 0 Myr corresponding to the present day. Positions of these groups linearly evolved through time, assuming the current velocity. The observer is positioned to the right of the image. An interactive version that allows the change in perspective, with the age slider of up to 12 Myr in either direction, is available online.

(An interactive version of this figure is available.)
I used the groups that have complete phase space information, i.e., radial velocities either from APOGEE or from Gaia are available for some stars in the group. Paper I measured the average age of the stars for each group: Age$_{HR}$ was used, when available (as it has been extinction corrected), otherwise, Age$_{CMD}$ was used. In Figure 2 I show a 3D traceback model of Orion, where different groups are at a particular time, ranging from 12 Myr in the past, to 12 Myr in the future (in the interactive version of the plot). Different groups are added only at the time corresponding to their ages and are excluded from the previous timestamps.

This traceback is quite simplistic. It does not account for the self gravity of the Complex, either stars or gas. No two groups are able to interact, even when they are both components of the same cluster (i.e., although the subgroups composing the ONC appear to fly apart in the traceback going far enough into the future, it is unlikely to happen in reality). Furthermore, no new stars are able to form. Nonetheless, it does show the general patterns of motion; that the expansion of the Complex all indeed appears to originate from the same point; and that it is largely spherical, with the dominant plane for the stellar distribution.

Figure 3 further demonstrates the expansion, reducing the 3D motion of the individual groups to 1d distance to the apparent center of the expansion. Although they do not necessarily all converge to zero (due to uncertainty in parallax; uncertainty in correction for the average position and velocity; physical sizes of the groups themselves; velocity dispersion within the group; self gravity of the Complex affecting the trajectory; as well as the initial geometry of the cloud), the minimum size of the expanding populations indeed occurs ~6 Myr ago. Furthermore, the majority of star formation has occurred after this time.

Putting all of these pieces together, it becomes evident that the radial expansion of the Orion Complex from the geometrical center of Barnard’s loop and the formation of the H II bubble itself is likely attributable to the same event. Moreover, there are many similar hallmarks in the velocity structure and the H II bubble compared with λ Ori. From these dynamics I propose that a supernova that erupted ~6 Myr is the most likely cause. As is the case with λ Ori, a supernova is the primary event capable of accelerating the gas and stars to the appropriate speeds and produce the structure of the current size, as other forms of stellar feedback do not have sufficient force. Although a number of other H II bubbles are present in the Orion Complex that are caused by photoionization and winds from OB stars, they tend to be only a few pc in diameter and have a clear driving source. A lack of a suitably bright and massive star at the epicenter of the expansion, despite a clear spherical geometry, further suggests that while such a driving source most likely have existed in a past, it has since died off.

Recently, Großschedl et al. (2020) have also independently identified a episode of major feedback event in the Orion Complex dating back 6–7 Myr ago, which they refer to as Orion-6 event, using different tracers. They suggest that the most likely origin of this event is the Orion X region, which is an overdensity of stars in Orion D located somewhat south of η Ori. Although, currently Orion X is located in one of the expanding shells, its line of sight is indeed consistent with the center of the bubble, and 6 Myr ago it would have been much closer in the 3D space as well. Better determination of stellar ages is needed to confirm if it could have formed the progenitor, or if it has been one of the first regions formation of which would have been assisted by the shockwave.

However, rather than a single event, Großschedl et al. (2020) suggest that it might have been a result of multiple triggers that continued over time, which might explain the difference in momentum of the different clouds. While self gravity of the Orion Complex may explain some of these differences, it may be difficult to discriminate between a single explosive event and a group of neighboring events that occurred close in time. Future simulations, such as some of the ones noted in Großschedl et al. (2020), would be able to more definitively address this point.

4. Monogem Ring

In examining the ROSAT X-ray maps of the region (Snowden et al. 1997), two features are apparent (Figure 4). One, located to the west of Orion, is the emission associated with the Orion–Eridanus Superbubble, and it is thought to be related to the winds or the supernovae from the Orion Complex (Ochsendorf et al. 2015). This bubble is found at the distance similar to the Complex, and so low below the Galactic plane that no other population can be found that could serve as a likely progenitor. Indeed, even more complex clustering analyses akin to Kounkel & Covey (2019) do not reveal any overdensities in the phase space inside the superbubble.

Another X-ray feature is located to the east of Orion in the Monogem ring. It is commonly thought of as a supernova remnant (Plucinsky et al. 1996; Knies et al. 2018), with an estimated age of 0.068 Myr. It has a pulsar near its center, PSR B0656+14, with a spin-down age comparable to this estimate (Thorsett et al. 2003). Both Monogem and PSR B0656+14 are thought to be located at the distance of ~300 pc (Golden et al. 2005).

Similarly to the Orion–Eridanus Superbubble, due to its height above the Galactic plane, no young stellar population in
vicinity that could serve as progenitors can be associated with Monogem. Although some stars have been proposed to form such a population (Knies et al. 2018), with the revised Gaia astrometry compared to Hipparcos, no coherence in their phase space is apparent.

Nonetheless, if we assume that the proper motions of the pulsar measured with the Very Long Baseline Array (Golden et al. 2005) are representative of what the star that produced it originally had, then it may have originated from the Orion Complex as a runaway. Converting the proper motions to the LSR reference frame, the most likely origin is the λ Ori Cluster, ~1.7 Myr ago. Thus, if Monogem is a supernova remnant, it is also related to Orion. PSR B0656+14 is the second pulsar that could be traced back to Orion. Geminga is also a neutron star that likely have formed from a dynamically ejected runaway, originating from 25 Ori cluster ~1.3 Myr ago (Faherty et al. 2007).

The relative configuration of Monogem and Orion–Eridanus superbubble, with the Orion Complex positioned equidistantly in between them, ~200 pc apart, does appear to be somewhat peculiar. The two are located at similar distances from Earth as well, and have a somewhat similar morphology and size on the sky. They are evocative of a bipolar outflow that may have been associated with Barnard’s loop supernova. Further investigation would be needed in the future to explore this possibility. In particular, the increased sensitivity, as well as spectral and spatial resolution of eROSITA may be of benefit in establishing relationship between these two features.

5. Discussion

It is notable that the stellar density distribution of the Orion Complex appears to be continuous from the bottom of Orion A, up to ζ² Ori (possibly up to λ Ori, after a small gap), as though forming one long filament. This filament is made less apparent by the stars that are expanding away from the Complex, near Rigel and near L1616, although they would have originated from the filament also. Furthermore, there are a number of outlying clouds and populations, some fairly massive (namely Orion B) some significantly less so (see Figure 1) that are infalling toward the Complex. Although they are excellent examples of the gravity at work, they act as deterrents in visualizing a simplistic model of the Complex, requiring a conceptual separation of these regions, as their formation and their kinematics are driven by different mechanisms compared to the main filament.

Because Orion A and B molecular clouds have been a cornerstone in our understanding of star formation, it is easy to think of them as discrete and complete units, the entire clouds coalescing at the same time, that what we see of them now is all there ever was, and that while other clouds would have existed in the vicinity, they would have always been separate entities. However, recent studies of the solar neighborhood have found a number of stellar strings: large structures composed of comoving stars extending for several hundred parsecs in length and only a few parsecs in width, resembling filamentary molecular clouds from which these stars likely to have formed and retained their morphology long after the gas is dispersed (Kounkel & Covey 2019). Moreover, these strings appear to be a dominant form of star formation, accounting for most of the stars that are found in comoving groups up to an age of ~100 Myr. With this in mind, it becomes possible to imagine the entire Orion Complex as one string formed from the same molecular filament (or perhaps a narrow sheet of gas). While Orion A is the southern part of this filament that still exists in the molecular gas form, and it had recently has reached densities large enough to start forming stars, the northern part of the same filament has became Orion C & D and has dispersed its gas. On the other hand, Orion B is quite distinct from the rest, not part of the same filament, but rather it is in the process of infalling toward it.

The shockwave of the erupting supernova would have been able to sweep the molecular gas and segment the filament. The northern part has already started actively forming stars for >2 Myr at that point. Most likely, the deceased star has been among those newly formed, although it could have been a leftover from the previous generation of star formation in the region (e.g., Jerabkova et al. 2019b).

Whether it is due to asymmetries in the distribution of gas, the location of star relative to the filament, or both, the gas has been propelled primarily in three directions, producing the current geometry of the Orion Complex that has analogues in the simulations of supernovae in giant molecular clouds (e.g., Smith et al. 2020). Two shockwaves were propelled toward the front and toward the back of the filament, relatively rapidly consuming already partially depleted gas as Orion C & D begin to take form as separate entities. The gravitational feedback (Zamora-Avilés et al. 2019) may have also assisted in this process. Meanwhile, the third shockfront has been pushed back into the southern part of the filament that was at the time just beginning to collapse (Figure 5). Although its original density likely been comparable in what is found in L1641, the shockwave could have accumulated the gas from several pc into a single concentrated region. The line-of-sight separation between the ONC and the proposed eruption site is ~10 pc. Such a rapid piling of gas could have lead to the formation of the singularly most massive young cluster in the Solar Neighborhood.

This could also explain the uneven distribution of ages in the cluster (i.e., while older stars are found throughout the head of Orion A, the younger ones are concentrated at the center of the cluster Beccari et al. 2017). Although it can be argued whether these generations of stars correspond to the discrete events
(Jerabkova et al. 2019a), or that the distribution of ages is more continuous (Da Rio et al. 2010; Olney et al. 2020), as the cluster continued to sweep through the filament, it would have had access to more gas to support several generations of stars, in a “conveyor belt” manner (Krumholz & McKee 2020). And, although the initial sweep of gas would have allowed star formation along the entire width of the filament, subsequently the self gravity of the forming cluster would have become more important.

Eventually, as the density of the accumulated gas would have been sufficiently high, and the pressure behind the shockwave decreased as it expanded out further, the momentum of the ONC traveling through the filament was able to decrease, allowing the front to pass through.

The model does not explain the formation of Orion B molecular cloud or other less massive infalling clumps of gas. Orion B is the only one of these clouds through which the shockwave begins to be split and compressed. Star formation in Orion C & D continues as they separate. Beginning of the compression of the gas in the direction of the filament, seeding the formation of the ONC. Right: The molecular gas in Orion C & D has been largely dissipated, as the stars inside them continue spherical expansion. The ONC becomes massive. L1641 becomes dense enough to begin forming stars.

Figure 5. Conceptual model of the formation of the Orion Complex, excluding Orion B and λ Ori. Black contours represent the molecular gas, red dots are the stars. The observer is located to the right of the image, direction indicated by the arrow. Left: early epoch of star formation in the filament. Middle: post supernova eruption, the filament begins to be split and compressed. Star formation in Orion C & D continues as they separate. Beginning of the compression of the gas in the direction of the filament. Right: The molecular gas in Orion C & D has been largely dissipated, as the stars inside them continue spherical expansion. The ONC becomes massive. L1641 becomes dense enough to begin forming stars.

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Software: TOPCAT (Taylor 2005), Plotly (Inc., 2015).

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