

Overview of the Orion Complex

John Bally

*Center for Astrophysics and Space Astronomy, University of Colorado
Boulder, CO 80389, USA*

Abstract. The Orion star formation complex is the nearest region of on-going star formation that continues to produce both low and high mass stars. Orion is discussed in the larger context of star formation in the Solar vicinity over the last 100 Myr. The Orion complex is located on the far side of the Gould's Belt system of clouds and young stars through which our Solar system is drifting. A review is given of the overall structure and properties of the Orion star forming complex, the best studied OB association. Over the last 12 Myr, Orion has given birth to at least ten thousand stars contained in a half dozen sub-groups and short-lived clusters. The Orion OB association has been the source of several massive, high-velocity run-away stars, including μ Columbae and AE Aurigae. Some of Orion's most massive members died in supernova explosions that created the 300 pc diameter Orion / Eridanus super-bubble whose near wall may be as close as 180 pc. The combined effects of UV radiation, stellar winds, and supernovae have impacted surviving molecular clouds in Orion. The large Orion A, IC 2118 molecular clouds and dozens of smaller clouds strewn throughout the interior of the superbubble have cometary shapes pointing back towards the center of the Orion OB association. Most are forming stars in the compressed layers facing the bubble interior.

1. Introduction

Orion is the best studied region of star formation in the sky. Its young stars and gas provide important clues about the physics of star formation, the formation, evolution, and destruction of star forming clouds, the dynamics and energetics of the interstellar medium, and the role that OB associations and high mass stars play in the cycling of gas between the various phases of the ISM.

In this chapter, we start with an overview of the Solar vicinity that establishes the context in which nearby star forming regions must be understood. Then we discuss the Orion complex of star forming regions as an example of star formation in an OB association.

2. Spiral Arms, Superbubbles, GMCs, and Star Formation in the Solar Vicinity

The Solar vicinity (within about 0.5 to 1 kpc of the Sun) is the only place where it is possible to investigate the distributions and motions of young stars and associated gas in 3 dimensions and to probe the history of star formation and the interstellar medium (ISM). While HII regions and low mass T-Tauri stars trace the youngest (< 3 to 5 Myr old) sites of on-going or recent star formation, OB associations can trace star formation history back nearly 100 Myr. The least massive stars that end their lives in supernova explosions have masses of about $8 M_{\odot}$, main-sequence lifetimes of about 40 Myr, and

spectral type B3 which can excite small HII regions. Thus, groups containing B3 and earlier type stars trace sites of star birth younger than 40 Myr. OB associations whose most massive members have later spectral types can identify locales where stars formed more than 40 Myr ago. The mass spectra, locations, velocities, and ages of young stars and the properties of gas in nearby associations provide clues about the history of star formation and the origin, evolution, and destruction of molecular clouds over the last 100 Myr. Such studies enable us to decode the recent history of the interstellar medium and associated star birth in our portion of the Galaxy.

Currently, the Solar vicinity appears to be located in an inter-arm spur of gas and dust between two major spiral arms of the Galaxy. Looking towards the Galactic anti-center, the Perseus Arm lies about 2 kpc beyond the Solar circle. Many well-known star forming complexes are embedded in this arm. They include giant cloud complexes near $l = 111^\circ$ that contain NGC 7538 and the Cas A supernova remnant, the W3/W4/W5 complexes near $l = 134^\circ$, and the Auriga and Gem OB1 clouds in the anti-center direction (see chapters by Kun et al., Megeath et al., and Reipurth & Yan). Looking towards the inner Galaxy, the Sagittarius Arm is located about 2 kpc inside the Solar circle and contains the M8, M16, and M17 star forming complexes, see chapters by Tothill et al., Oliveira, and Chini & Hoffmeister. Millimeter-wavelength molecular absorption against the Galactic center clouds shows that the Sagittarius arm has a blueshifted radial velocity of $V_{LSR} = -15$ to -20 km s $^{-1}$. The more distant Scutum and 3 kpc Arms appear at $V_{LSR} = -35$ and -60 km s $^{-1}$.

Superimposed on Galactic differential rotation, most of the ISM in the Solar vicinity (GMCs and HI) is expanding with a mean velocity of 2 to 5 km s $^{-1}$ from a point located near $l = 150^\circ$, $b = 0^\circ$, $d = 200$ pc, the approximate centroid of the 50 Myr old Cas-Tau group, a ‘‘fossil’’ OB association (Blaauw 1991). This systematic expansion of the local gas was first identified by Lindblad (1967, 1973) and is sometimes called ‘Lindblad’s ring’ of HI, but it is even more apparent in the kinematics of nearby molecular gas (Dame et al. 1987, 2001; Taylor, Dickman, & Scoville 1987; Poppel et al. 1994). The Sun appears to be well inside this expanding ring. The nearest OB associations, such as Sco-Cen ($d \approx 150$ pc), Per OB2 ($d \approx 300$ pc), Orion OB1 ($d \approx 400$), and Lac OB1b ($d \approx 500$ pc), and the B and A stars that trace the so-called ‘Gould’s Belt’ of nearby young and intermediate age stars are all associated with Lindblad’s ring (Lesh 1968; De Zeeuw et al. 1999). Lindblad’s ring appears to be a 30 to 60 Myr old fossil supershell driven into the local ISM by the Cas-Tau group and the associated α Persei cluster (Blaauw 1991). The Gould’s Belt of stars, nearby OB associations, and star forming dark clouds may thus represent secondary star formation in clouds that condensed from the ancient Lindblad ring supershell. Figure 1 shows a schematic face-on view of the Solar vicinity. Support for this view comes from the agreement between the observed radial velocity fields of the local HI emission and nearby CO clouds (Figure 2) with models of an expanding and tidally sheared 30 to 60 Myr old superbubble powered by the Cas-Tau group (Poppel et al. 1994).

The distribution of dust in the COBE and IRAS data and the kinematics of high-latitude HI provide additional evidence for an ancient super-shell created by a superbubble centered on the Cas-Tau group that swept-up the local ISM, and blew out of the Galaxy orthogonal to the Galactic plane. The lines of sight with the lowest column densities of HI (the Lockman Hole; Figure 12 in Stark et al. 1992) and dust (Baade’s Hole) lie above and below the Cas-Tau group near $l = 150^\circ$ and $b \pm 35^\circ$, providing

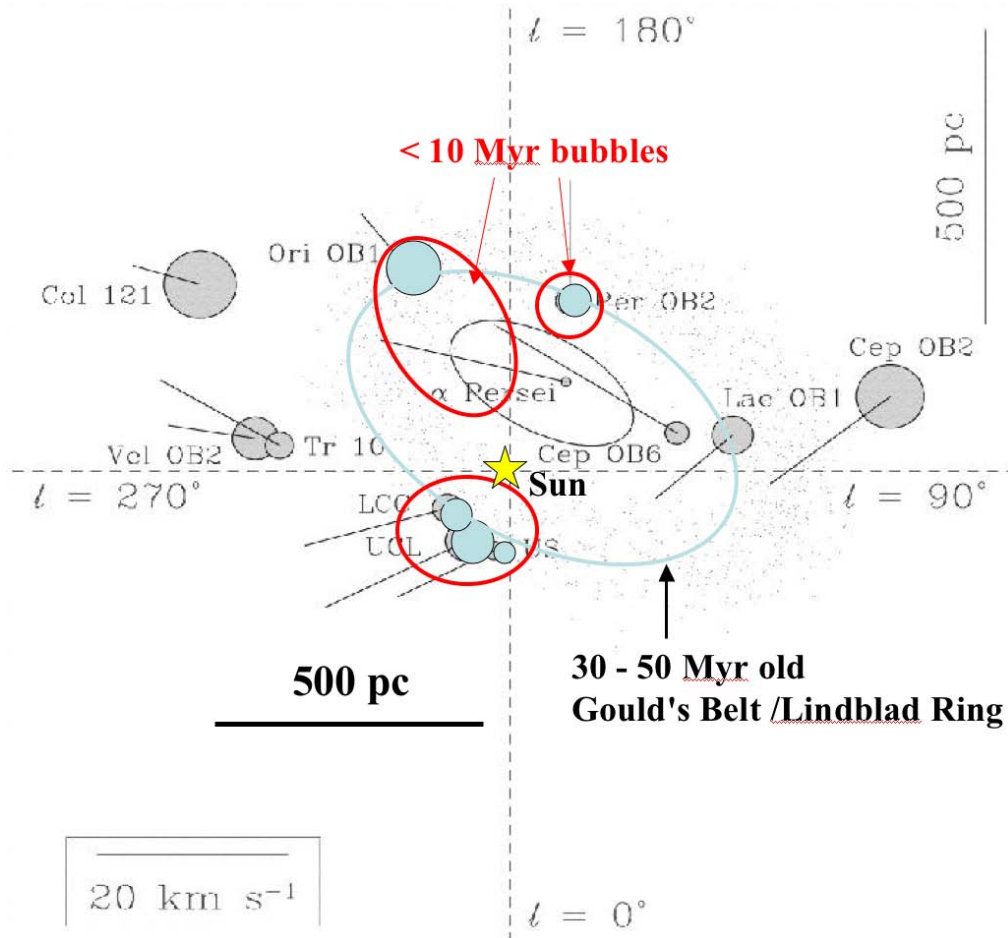


Figure 1. A Sun-centric schematic face-on view of the Solar vicinity showing the older OB associations from de Zeeuw et al. (1999; solid grey disks), the approximate location of the Lindblad Ring, (blue oval) and the three major OB associations younger than about 20 Myr; Sco-Cen, Per OB2, and Orion OB1 (solid blue disks). The approximate outer boundaries of the supershells powered by each young association are shown as red ovals. The Cas-Tau fossil OB association whose center is marked by the α -Persei cluster, is marked by the grey oval inside the Gould's Belt / Lindblad Ring.

evidence that an ancient bubble burst out of the Galactic plane at about one dust scale-height above and below the Cas-Tau “fossil” OB association.

Gas expelled from the Galactic disk 20 to 50 Myr ago is now expected to be falling back. Indeed, the 21 cm line profiles formed by averaging all HI emission produced in both the northern and southern Galactic hemispheres show excess emission at low negative velocities in the range $v_{\text{lsr}} = -10$ to -40 km s $^{-1}$ (Stark et al. 1992) indicating an excess of infalling material at low velocities. Since the ambient pressure of the ISM orthogonal to the Galactic plane declines as an exponential, an expanding pressure driven supershell will accelerate once its radius becomes larger than the gas layer scale-height. As a supershell bursts out of the Galactic plane, it is subject to Rayleigh-Taylor

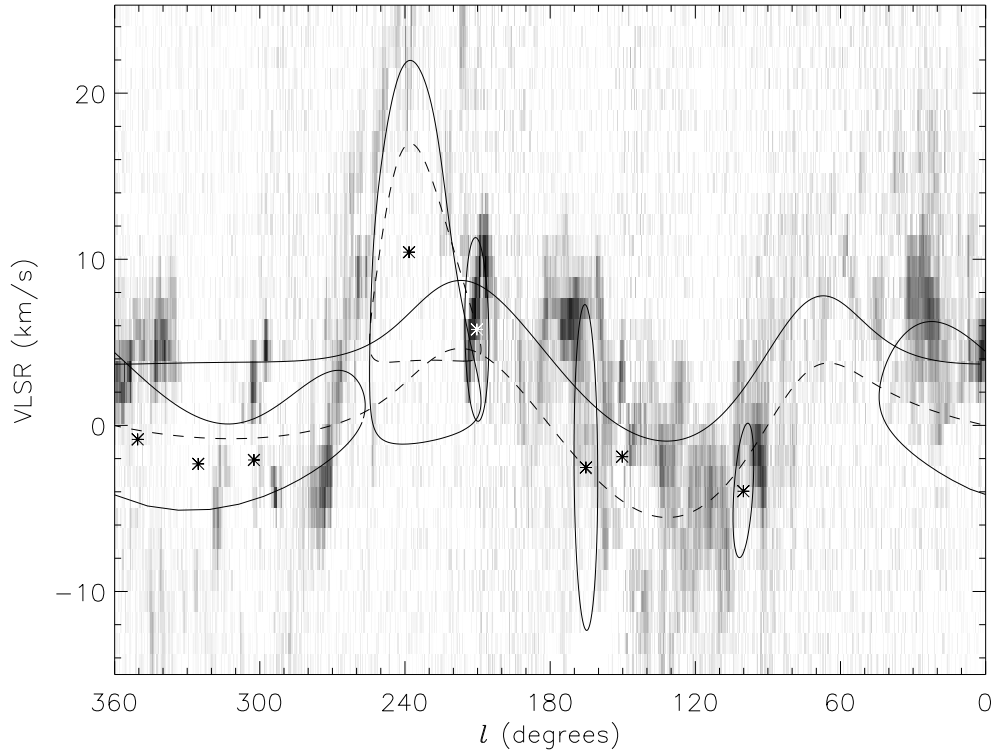


Figure 2. The location of CO clouds in the l - v plane with brightness temperature shown in grey-scale (the CO data are from Dame et al. 1987). To reduce confusion from distant gas in the disk, emission with $|b| < 2.0^\circ$ is not shown. The location of the nearby OB associations are shown by asterisks (*). Association velocities are derived from their longitudes, distances, and the Galactic rotation curve. Included are Orion at $l = 210^\circ$, Sco-Cen at $l = 300^\circ$ to 360° , Per OB2 at $l = 165^\circ$, Lac OB1 at $l = 100^\circ$, the α Persei cluster at $l = 150^\circ$, and the expected location of the association that created GSH238-00+9 (Heiles 1998). Models of the supershell powered by the “fossil” Cas-Tau group (centered near the α Persei cluster) are shown by two curves extending horizontally across the figure. Models of the younger supershells are shown by the closed loops. Dashed lines show the expected velocity fields of stationary supershells assuming that their velocities reflect *only* the motion produced by Galactic differential rotation (e.g. the shells are not expanding). The solid lines show the velocity fields produced by both *Galactic differential rotation* and *expansion* powered by the energy released by OB stars. For the Gould’s Belt/Lindblad ring, an expansion velocity of 4.5 km s^{-1} is assumed from a point located about 170 pc from the Sun towards $l = 131^\circ$. While this is 20 degrees from the estimated center of the Cas-Tau fossil association, the original position of Cas-Tau is uncertain due to its 200 pc extent along the Galactic plane at a distance of 160 pc and because a small ($\approx 4 \text{ km s}^{-1}$) peculiar velocity could have moved it this angular distance during the past 15 Myr. The expansion velocities used for the other bubbles are 5.0 km s^{-1} for the “NSB” (GSH238+00+09) identified by Heiles at $l = 240^\circ$, 5.0 km s^{-1} for Sco-Cen, 5.0 km s^{-1} for Orion, 10.0 km s^{-1} for Perseus, and 4.0 km s^{-1} for Lac OB1.

fragmentation instabilities (MacLow & McCray 1987). After blow-out, the resulting dense clumps will move ballistically in the gravitational potential of the Galactic disk. Up to about 500 pc above the plane, the gravitational field of the disk is reasonably well represented by a harmonic oscillator potential with a z -oscillation time of about 80 to 100 Myr (Spitzer 1978). Clumps ejected from near the Galactic plane at less than 40 km s^{-1} will stop at heights of less than 500 pc within 20 – 25 Myr of their formation. During the next 20 – 25 Myr, they fall back towards the plane. Thus, the dynamical age of the low velocity infalling HI is comparable to that of the Cas-Tau group. Figures 3 and 4 show a schematic view of super-bubble, super-shell, and super-ring evolution.

In summary, the Sun appears to be in the interior of an ancient supershell that may have produced the parent clouds from which Orion and most of the other nearby star forming regions originated. There are several lines of evidence to support this view:

- The expanding network of HI clouds (the Lindblad Ring) and associated molecular clouds.
- The Gould's Belt of young stars that appears to be associated with the Lindblad Ring.
- The locations of the lowest column densities of dust and HI are situated above and below the centers of the ring.
- The excess of infalling, low negative velocity HI towards the North and South polar caps of the Galaxy.
- The presence of the Cas-Tau fossil OB association and its central cluster, the α -Per group.

The age of the Cas-Tau group, estimated to be between 40 to 90 Myr, may indicate that it formed when the Solar vicinity made its last passage through a major spiral arm of the Galaxy. Since the density of gas is higher in an arm, it is likely that so too was the star formation rate. Thus, the Cas-Tau group may have produced more stars and a larger super-bubble than the second generation clouds and OB associations such as the Sco-Cen and Orion OB associations, that were spawned from its super-ring. The stellar content of Cas-Tau remain poorly determined. Future parallax, proper motion, radial velocity, and spectroscopic surveys are needed to establish membership.

3. Stars in the Orion Complex

The Orion OB association consists of a sequence of stellar groups of different ages that are partially superimposed along our line-of-sight (see chapter by Briceno and Figures 5 and 6). Traditionally, OB sub-group boundaries have been drawn to segregate each into a well defined and contiguous regions on the plane of the sky (see chapter by Briceño). However, when various stellar aggregates are superimposed on the plane of the sky, it make sense to also incorporate ages into the sub-group classification. Although there are differences in the estimated ages of the various groups, most workers agree that the oldest group, Orion OB1a, is located northwest of Orion's Belt, and has an age of about 8 to 12 Myr (Blaauw 1991; Brown et al. 1994). The OB1b subgroup is centered on the Belt and has been estimated to have an age ranging from 1.7 to 8 Myr. However, the younger age is inconsistent with the presence of the three supergiants that form the naked-eye Belt stars which must be at least 5 Myrs old given their masses. A recently discovered cluster of roughly 7 to 10 Myr old stars is centered around 25 Ori at the northwestern end of Orion's Belt (Briceño et al. 2007). Although formally a part of the Orion OB1a sub-group, the 25 Ori cluster has a distinct radial velocity, being about 10

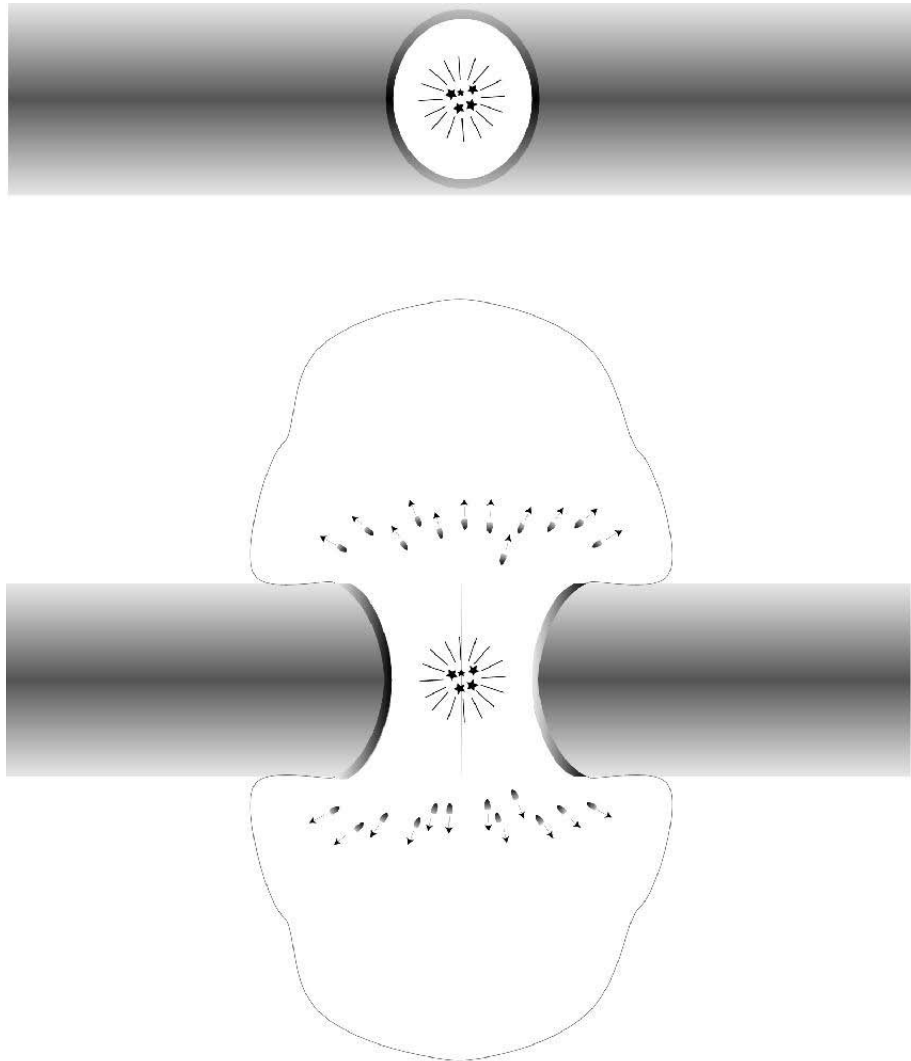


Figure 3. A schematic cartoon showing a super-bubble blowing out of the Galaxy during its early evolution (top). UV radiation, stellar winds, and multiple supernova explosions in the parent OB association inject energy at a roughly steady rate for about 40 Myr as stellar mortality depopulates the upper-end of the mass function down to a mass of $8 M_{\odot}$, the least massive star that can explode. The hot expanding bubble displaces ambient gas and sweeps it into a dense shell. As the swept-up shell reaches a radius larger than the scale-height of the gas layer, it blows out of the Galactic plane (bottom). The densest part of the shell forms a ring in the plane of the gas layer. As the shell expands into the exponentially declining density gradient above the plane, Rayleigh-Taylor instabilities can cause the shell to fragment into dense clumps at high latitudes.

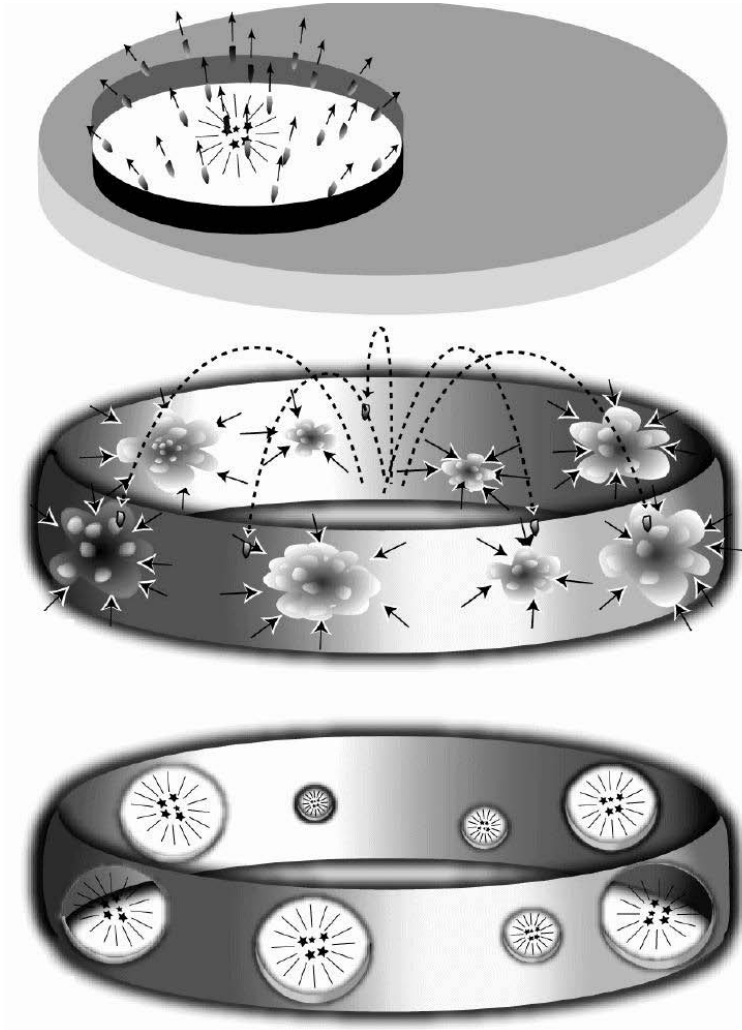


Figure 4. A schematic cartoon showing the late phases in the evolution of a super-bubble-driven super-shell and ring. Dense clumps formed at high latitudes (top) by instabilities in the expanding shell start to fall back towards the Galactic plane after 20 to 25 Myr due to the gravitational potential of the Galactic disk. To first order, the gravitational field of the disk in the Solar vicinity is well represented by a harmonic oscillator potential in the vertical direction that gives rise of oscillations about the mid-plane with a period of about 80 to 100 Myr. Thus, clumps created by fragmentation of the shell will tend to fall-back into the mid-plane in about 40 to 50 Myr. As the shell sweeps-up the ISM in the Galactic mid-plane and decelerates, the expanding ring of gas can become unstable to gravitational collapse (middle). This occurs when the local spreading velocity caused by shell expansion drops below the gravitational escape speed from that portion of the ring. For typical OB association and super-bubble parameters in the Solar vicinity, instabilities set in at a ring-age of about 30 to 50 Myr after formation. The first self-gravitating objects tend to have masses of order $10^5 M_{\odot}$ (McCray & Kafatos 1987). Note the similarity of time-scales on which high latitude debris returns to the plane and the onset of gravitational instabilities. These clumps may soon evolve into GMCs that form their own OB associations and new super-bubbles (bottom).

km s⁻¹ lower than the traditional members of the 1a subgroup. It has been proposed that the 25 Ori group was formed as the HII region created by the 1a subgroup expanded into surrounding gas and triggered a burst of star formation. The 25 Ori group may thus represent a group that formed between Ori 1a and 1b.

The 2 to 6 Myr old OB 1c subgroup consists of stars located in Orion's Sword about 4° below the Belt and directly in front of the Orion Nebula. This subgroup contains two loose clusters, NGC 1980 at the southern end of the Sword, and NGC 1981 at the northern end (Figure 6). The older stars in the Sword are superimposed on the much younger stellar populations associated with the Orion Nebula, M43, NGC 1977, and the OMC1, 2, and 3 regions in the Integral Shaped Filament at the northern end of the Orion A molecular cloud (see Figure 2 in the chapter by O'Dell et al.). Thus, it is hard to separate these two stellar populations and it is unclear whether the 1c and 1d subgroups represent different populations, or merely older and younger stellar groups that formed from the Orion A cloud at different times. See the chapter by Muench et al. for further discussion.

The λ Ori group (see chapter by Mathieu) may also have been triggered by the expansion of the bubble created by Orion OB 1a. This group has an age similar to the Orion OB 1b or the older stars in OB 1c and, as illustrated in Figure 5, the λ Ori group is located at approximately the same distance from the center of Ori OB 1a as Ori OB 1c. Thus, the λ Ori group could be considered to be a disjoint portion of OB 1c.

The sub-cluster of stars centered on σ Ori, located just below the eastern end of Orion's Belt (Figures 5 & 6), has been assigned to OB 1b based on its spatial proximity. However, the ages of the σ Ori stars indicate that it is considerably younger than most of the stars in the Belt region (Walter et al. 1997). Because of its similar age, I prefer to assign the loose cluster of 2 to 4 Myr old stars centered on σ Orionis about 1° south of ζ Ori at the east end of the Belt (see the chapter by Walter et al.) to the OB 1c sub-group.

The Orion Nebula Cluster (ONC) in the Orion A molecular cloud and NGC 2024 in the Orion B molecular cloud are the two largest clusters in the youngest subgroup (known as OB 1d) with ages less than 2 Myr (see chapters by Muench et al. and O'Dell et al. for the ONC and Meyer et al. for NGC 2024). In addition to these large clusters, the 1d subgroup contains a dozen smaller clusters and a background distribution of relatively isolated stars forming in cores throughout the Orion molecular clouds (e.g. NGC 2068 and 2071 in Orion B, see chapter by Gibb, and L1641, see chapter by Allen & Davis). Several thousand (mostly low mass) members of the OB 1d subgroup formed from the "integral shaped filament" (Bally et al. 1987; Johnstone & Bally 1999) in the northern part of the Orion A molecular cloud that contains the Orion Nebula. About 2,000 of these stars with ages < 10⁶ years are concentrated around the massive Trapezium stars in the Orion Nebula itself (Hillenbrand 1997). Hundreds more are forming in the dense OMC2 and 3 cores north of the Orion Nebula (see chapter by Peterson & Megeath). Finally, there are dozens of small, mostly cometary clouds spread around the Orion region that form small aggregates (see chapter by Alcalá et al.). Though the full membership of the OB association has not been established, between 5000 and 20,000 stars are likely to have formed in the Orion region within the last 15 Myr. The ages and locations of Orion's various subgroups indicate that star formation has propagated through the proto-Orion cloud in a sequential manner.

The older subgroups in Orion lie closer to us than the younger subgroups. While the distances to the brighter members of the older 1a and 1b subgroups range from 320

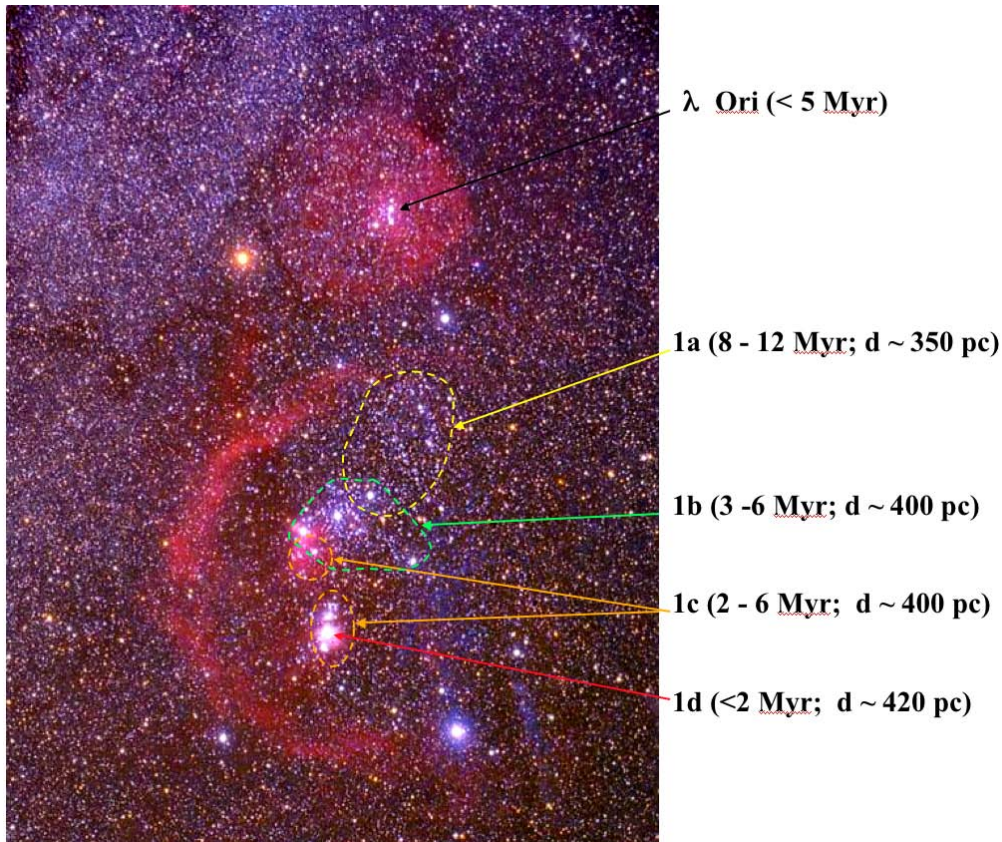


Figure 5. A wide field image showing Orion with the various sub-groups of the Orion OB1 association. Photo courtesy Wei-Hao Wang.

to 400 pc (Brown et al. 1994, 1995), the Orion Nebula was thought to lie at a distance of about 400 – 480 pc (Warren & Hesser 1977; Genzel et al. 1981). However, recent radio-parallax measurements using very long baseline interferometry indicate that the Orion Nebula is located at a distance of 437 ± 19 pc (Hirota et al. 2007), 389 ± 23 pc (Sandstrom et al. 2007), or 414 ± 7 pc (Menten et al. 2007), see detailed discussion in chapter by Muench et al. The 2 to 6 Myr old OB1c subgroup lies in front of the northern part of the Orion A cloud and the Orion Nebula. The absence of any obvious illumination or reflection nebulosity on the surface of the Orion A molecular cloud that can be attributed to massive members of the OB1c subgroup implies that this older subgroup must lie at least 10 pc in front of the Orion A cloud (see Figure 6).

It has been known for decades that run-away stars are common among O stars, rare among B stars, and virtually non-existent for later spectral types (Gies & Bolton 1986; Gies 1987). Orion has been the source of several well known run-away stars, including the 150 km s^{-1} run-away star AE Aurigae, and the 117 km s^{-1} μ Columbae which is moving exactly in the opposite direction (Blaauw 1991). Hoogerwerf, de Bruijne, and de Zeeuw (2001) used new Hipparcos proper motion data to show that these two stars, and the colliding wind X-ray binary ι Ori were at the same location in the sky 2.6 ± 0.05 Myr ago. Gualandris, Portegies-Zwart, and Eggleton (2004) argue that the

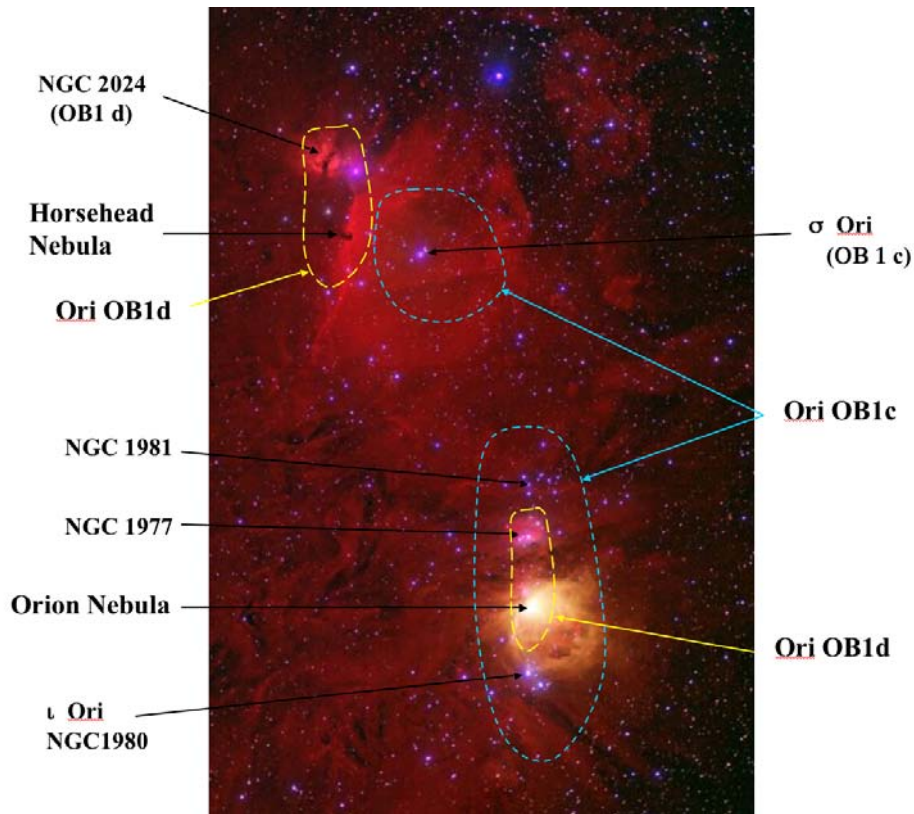


Figure 6. A close-up showing the southern portion of Orion that contains the OB1c and d sub-groups of the Orion OB1 association. Various clusters are marked. The older 1c subgroup is seen directly in front of the younger 1d sub-group. The image of Orion is courtesy M. Bissell and R.S. Sutherland.

two run-away stars and ι Ori suffered a four-body interaction in which two binaries in the same cluster underwent an exchange. The two most-massive members became the tight ι Ori binary; the gravitational energy released kicked the two less massive stars out of the region at high velocity. Figure 7 shows current configuration of these stars on a wide-field star-chart, along with the stellar motions traced back over time.

Interestingly, the proper motion of the Orion Nebula Cluster would place it at the location of the four-body interaction 2.6 Myr ago. The presence of some older stars in the Orion Nebula Cluster indicates that some star formation did occur in this region. However, the number of older stars indicate that star formation in the gas that created the ONC was much slower 2.6 Myr ago. Evidently the star formation rate in the ONC has been accelerating over time, culminating in the relatively recent formation of the Trapezium group of massive stars. Massive star formation continues to this day in the dense molecular ridge immediately behind the Orion Nebula.

The star ι Ori is embedded in an older, relatively dispersed cluster, NGC 1980, currently located at the southern end of Orion's Sword. NGC 1980 has been associated with the 1c sub-group of the Orion OB association located directly in front of the Orion Nebula and associated Orion A cloud. This dispersed cluster is located in the lower part of Figure 2 in the Chapter by Muench et al. in this volume and was designated as group

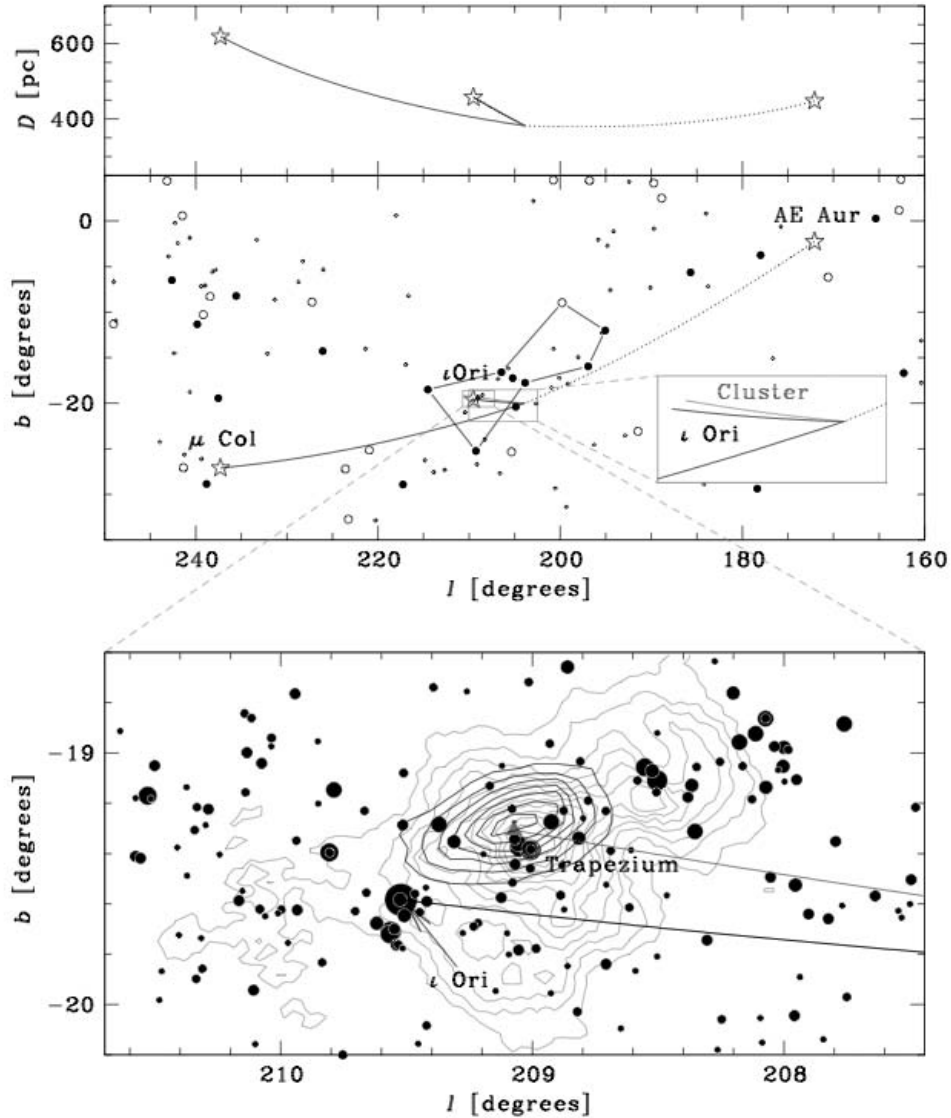


Figure 7. The run-away stars AE Aur and μ Col were ejected from the vicinity of the Orion Nebula about 2.6 Myr ago. Proper motions indicate that both the material that formed the ONC cluster in the Orion Nebula and the cluster NGC 1980 were co-located with point of origin of these runaway stars. The Orion Nebula and its stars had not yet formed. But the cluster NGC 1980 contains the colliding-wind X-ray binary ι Ori. Gualandris et al. (2004) claim this binary, and the ejection of the two run-away stars, formed when a four-member non-hierarchical massive star system in NGC 1980 decayed, forming the binary, and ejecting the two least massive members. Taken from Hoogerwerf et al. (2004).

V by Parenago (1954) and as Group 5 by Walker (1969) - see Table 2 in the chapter by Muench. The Orion OB1c sub-group also contains the cluster NGC 1981 located north of NGC 1977 and the Orion Nebula (see Figure 6). Assuming that NGC 1980 shares its motion through space with ι Ori, this cluster also would have been located in the same region as the material that later formed the Orion Nebula and rich cluster. Since ι is currently the most massive member of NGC 1980, this cluster is the most likely parent of the the two run-away stars AE Aur and μ Col. That the material that turned into the Orion Nebula and the ONC was apparently close to NGC 1980 several million years ago, suggests the intriguing possibility that the formation of the ONC and the Nebula may have been triggered by the older NGC 1980 cluster. If this hypothesis is correct, then the older stars in the ONC may in fact be outlying members of NGC 1980 and the Orion OB1c subgroup.

The locations and ages of stellar groups in the Orion region indicate that star formation can propagate through a cloud in a non-linear fashion. As first generation stars trigger the birth of subsequent generations, stellar groups with similar ages may be formed in spatially disconnected regions of the sky. In Orion, the 1a subgroup appears to be the first to have formed. Its massive stars may have induced the birth of the 25 Ori and 1b subgroups. Subsequent triggering may have induced further star formation in Orion's Sword to the south, σ Ori to the southeast, and possibly λ Ori to the north. Within the last few Myr, star formation propagated into the Integral Shaped Filament in the Orion A molecular cloud to form the Orion Nebula, M43, OMC2, OMC3, and NGC 1977, the "traditional members of the 1d sub-group located directly behind 1c. Recent star formation has also ignited east of Orion 1b and the σ Ori group to give rise to NGC 2023, NGC 2024, NGC 2068, and NGC 2071. Additionally, small stellar groups are forming from dozens of widely scattered cometary cloud strewn throughout the interior of the Orion super-bubble.

The lifetimes of the various molecular clouds in Orion remain unclear. Did the entire OB association form from a pre-existing giant cloud, or are the clouds formed rapidly by compression of the surrounding ISM as the super-bubble created by Orion's massive stars sweeps-up and compresses the medium? The structure and kinematics of the Orion A and B clouds and well as the dozens of smaller clouds in the region suggests that a "sweep-up, compress, and trigger" scenario may be at work. What roles did the massive run-away stars play in shaping the Orion super-bubble and in triggering cloud and star formation in distant regions? These issues will be addressed in the next section.

4. The Superbubble and Shell: Orion's Cloak

Massive stars inject energy into the ISM through their Lyman continuum radiation, stellar winds, and supernova (SN) explosions. If one assumes a standard IMF, then the estimated population of young stars in Orion implies that between 30–100 stars more massive than $8 M_{\odot}$ have formed in this region in the past 12 Myr. Many of these massive stars have evolved off the main sequence and exploded during the past 10 Myr. Using the age/mass relationship $\tau(M) = kM^{-\beta}$, with $\beta = 1.6 \pm 0.15$ in the mass range 8 to $80 M_{\odot}$ (Shull & Saken 1995), stars in the 1a subgroup more massive than about $13 M_{\odot}$ have exploded. For the 1b and 1c subgroups, a median age of 6 Myr implies that all stars more massive than about $20 M_{\odot}$ have exploded. Thus, there have been 10 to 20 SN explosions in the Orion region during the last 12 Myr.

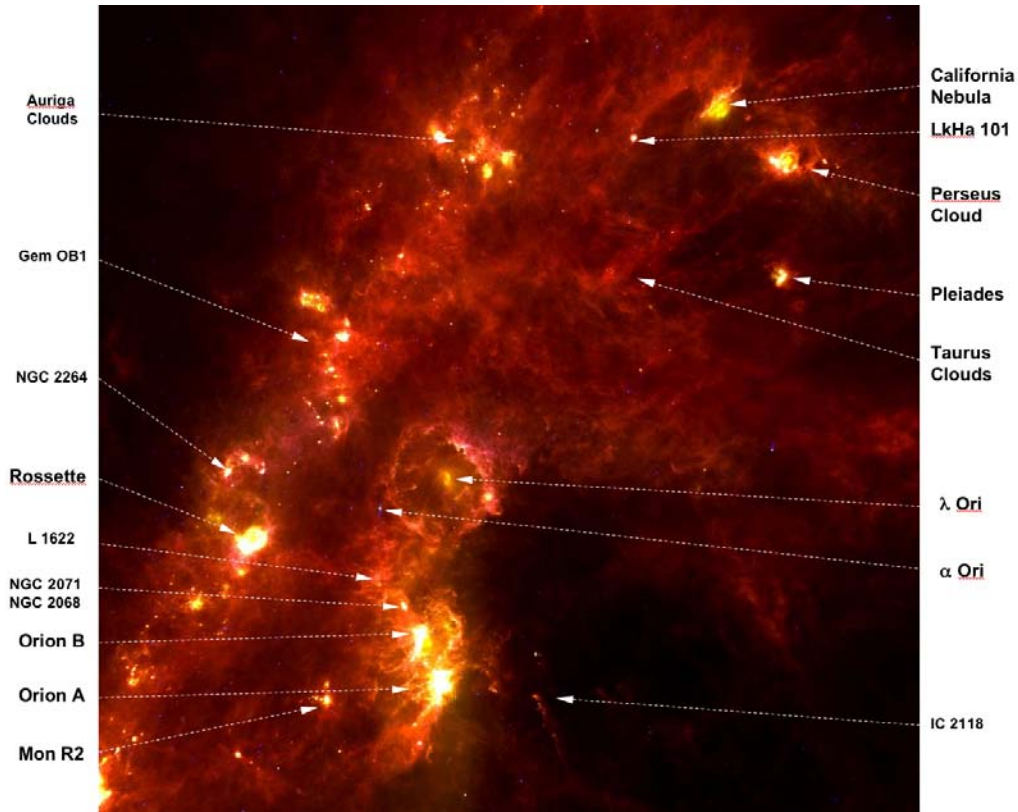


Figure 8. A wide field $100\ \mu\text{m}$ IRAS view of the Orion regions and its surroundings. Various star forming regions are marked. The IRAS map is courtesy Thomas Preibisch.

The released kinetic energy ($> 10^{52}$ ergs) has formed a large bubble of X-ray emitting gas whose expansion has swept-up a massive shell of gas and dust, the Orion/Eridanus superbubble.

Figure 8 shows a wide-angle view of the Orion region using the $100\ \mu\text{m}$ IRAS data which shows the distribution of warm dust. The Winter Milky Way stretches diagonally from the lower-left corner to the middle of the top boundary of the image; various well known star-forming complexes are marked. The brightest $100\ \mu\text{m}$ emission traces the warm dust associated with the young HII regions in Orion such as the Orion Nebula and NGC 1977 in Orion A, and NGC 2024 in Orion B. The spectacular λ -Ori ring is located just below and left of center. The dark region west of Orion A and B that dominates the lower right of Figure 8 traces the interior of the cavity excavated in the ISM by Orion/Eridanus superbubble.

Over 100 years ago, Barnard discovered a crescent of $\text{H}\alpha$ emission that wraps around the eastern portion of Orion (Figure 9). Sivan (1974) and Reynolds & Ogden (1979) demonstrated that Barnard's Loop is the brightest part of a giant bubble of $\text{H}\alpha$ emission that extends 40° west into Eridanus. The bubble subtends $20^\circ \times 40^\circ$, which at a distance of 400 pc corresponds to about 140 by 300 pc (Figures 9 and 10). The bubble appears to be blowing out of the Galactic plane since the OB association and its parent clouds lie about 15° to 20° (100 to 150 pc) below the plane. As a result, the

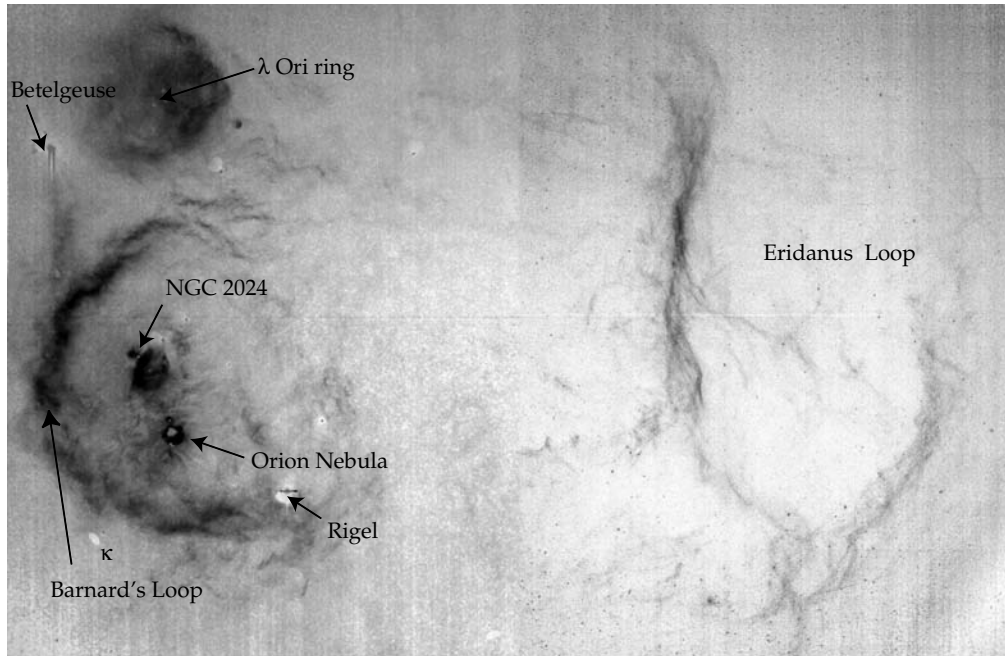


Figure 9. A continuum subtracted log intensity scale image of the Orion/Eridanus Bubble in $H\alpha$ showing a $30^\circ \times 47^\circ$ field of view. Images courtesy M. Bissell & R.S. Sutherland.

bubble is expanding into a steep density (and pressure) gradient with a mean velocity of order 10 to 20 km s^{-1} and may be evolving towards blow-out from the Galactic plane (Mac Low & McCray 1988). The $H\alpha$ bubble has a mass of about $M(\text{HII}) = 7 \times 10^4 M_\odot d_{380}^2$ (d_{380} is the distance in units of 380 pc) and a kinetic energy of at least $1.7 \times 10^{50} d_{380}^2$ ergs (Reynolds & Ogden 1979; Cowie et al. 1979; Burrows et al. 1993). The temperature in the bubble interior has been estimated to be 1 to $5 \times 10^5 \text{ K}$ from the excitation of UV lines and the presence of soft X-ray emission. It has also been detected in the 1.8 MeV γ -ray line of the short-lived radioactive species ^{26}Al , possibly indicating extensive recent pollution of the bubble interior by supernovae (Figure 11 and Diehl et al. 2004). Cowie et al. (1979) dubbed the hot gas in the interior of the Orion/Eridanus superbubble “Orion’s Cloak”.

The walls of the Orion superbubble are visible in the far infrared (Brown et al. 1995) and in 21 cm HI emission (Heiles 1976; Green 1991; Green & Padman 1993). Both tracers exhibit filamentary structure with most of the emission coming from a region located well outside the $H\alpha$ shell. The HI mass of the shell is about $2.3 \times 10^5 d_{380}^2 M_\odot$ and its kinetic energy is about $3 \times 10^{51} d_{380}^2$ ergs. Absorption measurements towards stars with known distances indicate that the near-wall of the Eridanus Loop may be as close as 180 pc from the Sun. Figure 12 show a possible geometry of the bubble and its walls. The proximity of this portion of the Orion/Eridanus Bubble and the presence of hot plasma may be an indication that a supernova exploded about midway between Orion and the Sun within the last few Myr.

Orion contains two $10^5 M_\odot$ giant molecular clouds; the Orion A cloud located behind Orion’s Sword in the southern portion of the constellation, and the Orion B

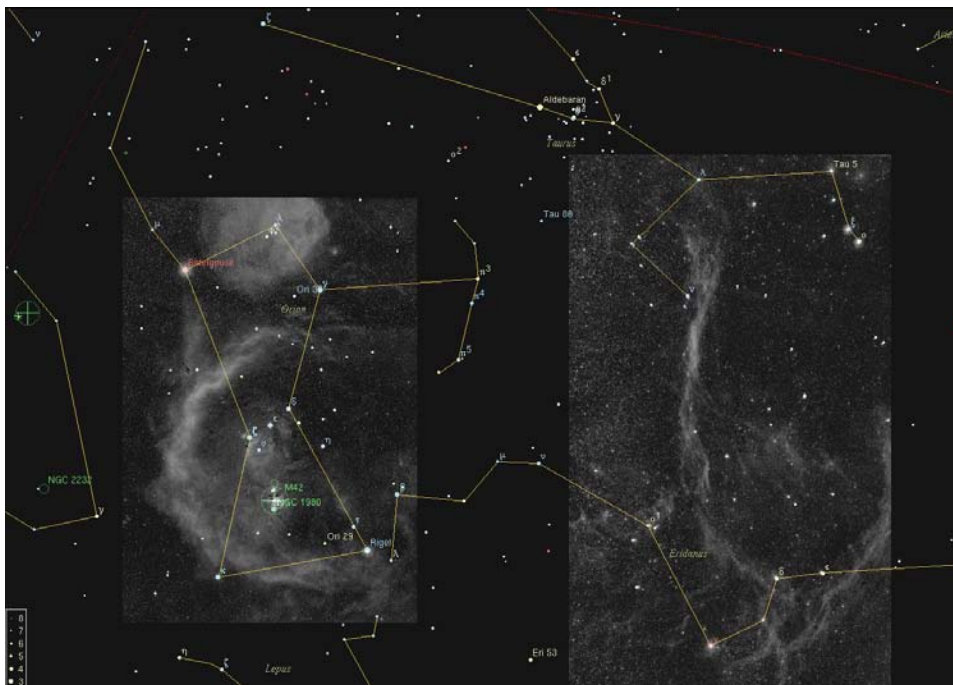


Figure 10. Wide-field $H\alpha$ images of the Orion / Eridanus bubble overlaid on a star chart. The image is shown in equatorial coordinates. Courtesy A. Mellinger.

cloud that lies east of Orion’s Belt. Both GMCs are located in the projected interior of the Orion/Eridanus superbubble (Figures 8 & 9) and appear to have been shaped by energy release from the Orion OB association (Maddalena et al. 1986; Bally et al. 1987; 1991a, b).

Orion A is cometary in appearance with a compact ridge of dense gas at the northern end (the “integral shaped filament”) and a lower density and wider tail that extends directly away from the centroid of the OB association. This cloud exhibits a large scale velocity gradient along its length; the northern part of the cloud is centered at $v_{\text{LSR}} = 11 \text{ km s}^{-1}$ while the southern part near κ Orionis has components with $v_{\text{LSR}} = 2 \text{ km s}^{-1}$. Bally et al. (1987) interpreted the smaller transverse extent and relatively high mean density of the gas in the north and the large scale velocity gradient as evidence for compression and acceleration by the OB association. Thus, star formation in the northern part of Orion A may be an example of triggering (Elmegreen 1997). Orion A may be forming at its southeast end as the ISM is swept-up and compressed by the advance of Barnard’s Loop; it may be destroyed by massive stars at its northwest end.

The Orion B cloud contains a high density ridge at its western end where the embedded clusters NGC 2024 and NGC 2023 and the Horsehead Nebula are located. A network of dust and CO filaments trails away from the OB association towards the east. The northern part of Orion B contains the NGC 2068 and NGC 2071 clusters that are embedded in dense cores at the southwestern ends of cometary clouds of CO emission. These clouds also trail off in a direction pointing away from the OB association.

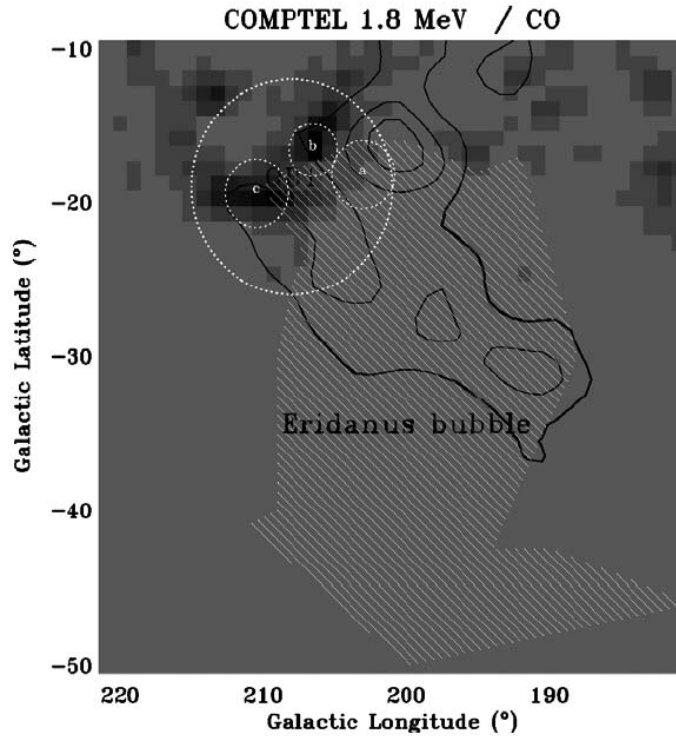


Figure 11. Wide-field view of the Orion / Eridanus bubble showing contours of 1.8 MeV gamma-ray emission from decays of ^{26}Al measured by COMPTEL (black contours), superimposed on a very low resolution CO map from Dame et al. (2001) shown in grey-scale. The white hatched area shows the location of the Orion-Eridanus cavity. The locations of the Orion OB1a, 1b, and 1c subgroups of the Orion OB association are shown in white. Taken from Diehl et al. (2004).

Dozens of smaller cometary clouds scattered throughout the interior of the Orion superbubble also have tails that point directly away from the Orion OB association. While a few of these clouds have velocities similar to the Orion A and B GMCs, the ensemble of small clouds in Orion has a large velocity dispersion that extends over a range $> 20 \text{ km s}^{-1}$. While this is far higher than the velocity dispersion of the Orion A and B clouds, it is smaller than the range of $\text{H}\alpha$ radial velocities associated with the $\text{H}\alpha$ shell. The CO velocities of the cometary clouds may indicate that the more massive fragments have suffered less acceleration while the smaller fragments either suffered larger accelerations or condensed from the tenuous HI gas comprising the expanding Orion/Eridanus superbubble.

Figure 13 shows several dozen cometary clouds located about 5° west of the Orion A cloud. The large cloud on the right side of this image is the IC 2118 cloud complex lit-up by Rigel. The large-scale structure of IC 2118 is a giant cometary structure with a major axis pointing back towards the older (10 Myr) Orion OB1a subgroup that lies about 5° to 8° to the northeast. Both the Orion A cloud and IC 2118 point to the OB1a subgroup. However, individual sub-condensations, especially on the eastern side of IC 2118, have axes of symmetry that point towards the northern portion of Orion A where the foreground OB1c and youngest OB1d subgroups are located. It

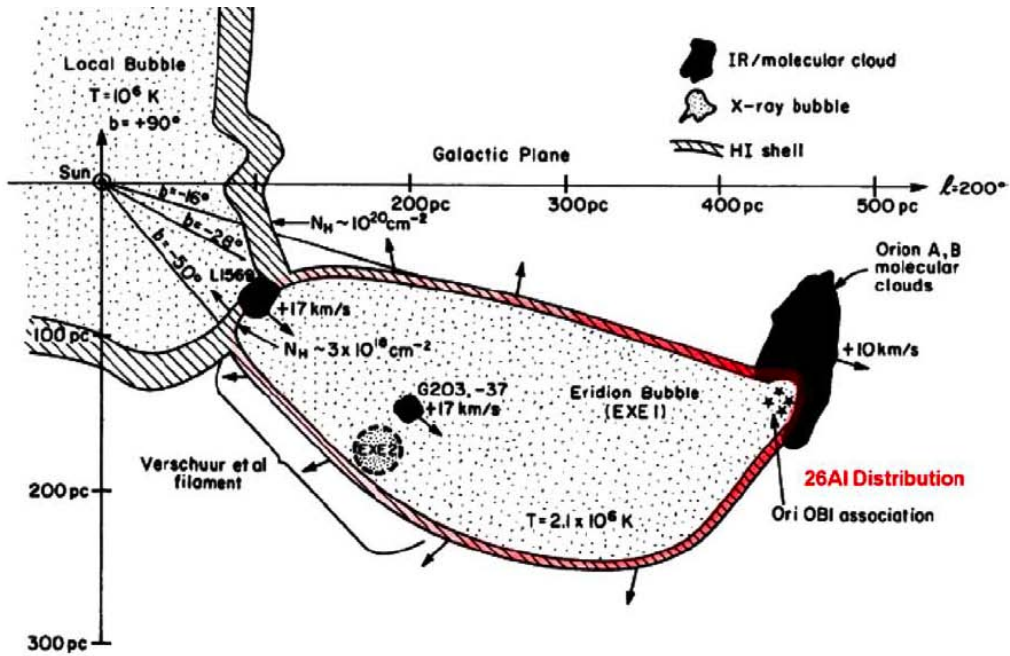


Figure 12. A cartoon showing the geometry and location of the Orion / Eridanus bubble relative to the Sun and the Orion molecular clouds. Taken from Diehl et al. (2004).

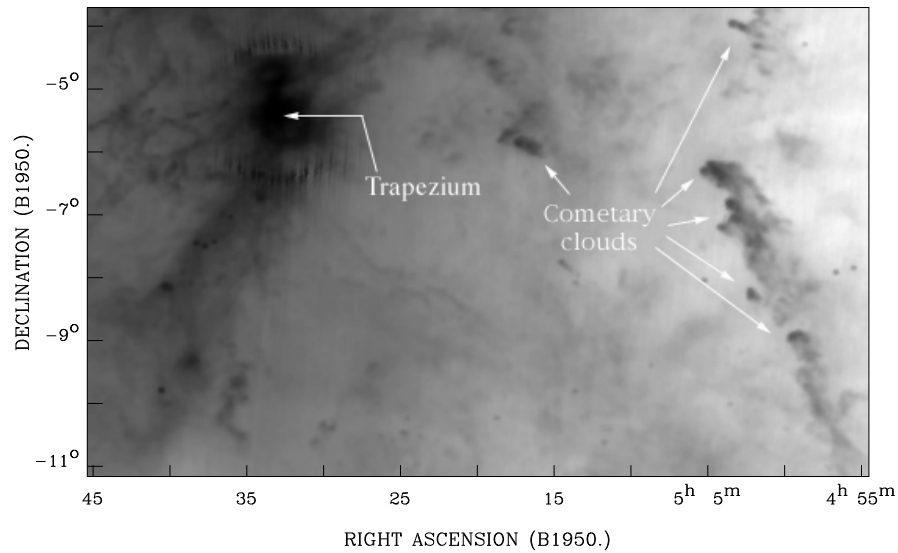


Figure 13. An IRAS 100 μm view (log scaling) of a family of cometary clouds located about 5° west of the Orion A cloud. The dark region extending southeast of Trapezium is the Orion A cloud. The cometary cloud above the center of the image is L1634. IC 2118 consists of the cometary clouds near the right edge of the image.

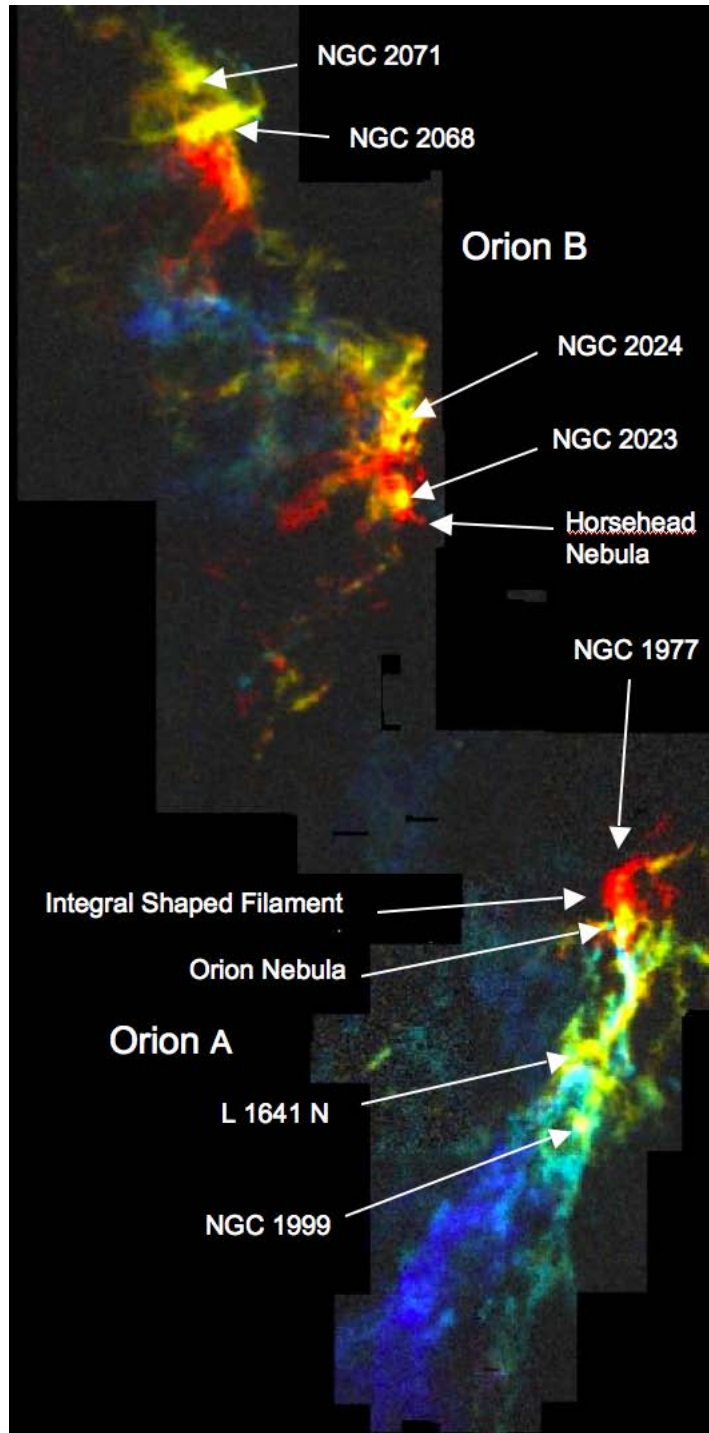


Figure 14. A 110 GHz ^{13}CO J=1-0 image showing the Orion A and B clouds. The colors represent Doppler shifts with blue corresponding to $V_{LSR} = 0$ to 5 km s^{-1} , green corresponding to $V_{LSR} = 5$ to 10 km s^{-1} , and blue corresponding to $V_{LSR} = 10$ to 15 km s^{-1} . Data were obtained during the mid 1980s with the 7 meter radio telescope located on Crawford Hill in Holmdel, NJ. (see Bally et al. 1987).

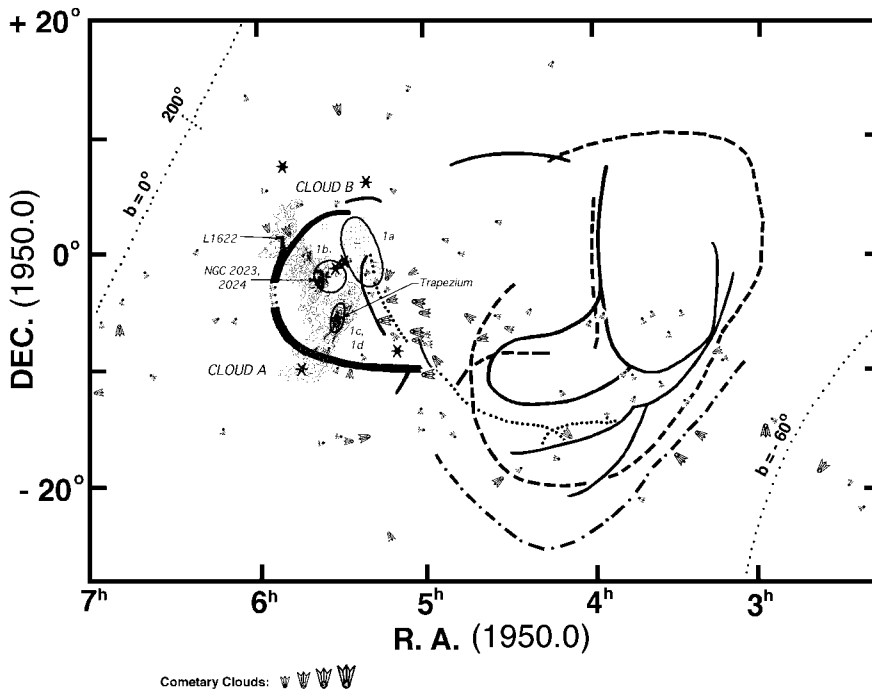


Figure 15. A cartoon showing the locations of cometary clouds detected using IRAS $100\ \mu\text{m}$ emission from warm dust. The faint solid contours show the location of the Orion A and B clouds shown in detail in Figure 14. The thick solid lines show the location of the brightest $\text{H}\alpha$ emission from Figures 9 and 10. The dashed and dot-dashed lines show the location of ridges of 21 cm HI emission thought to be associated with the Orion-Eridanus bubble.

is likely that initially, this cloud complex was shaped by UV radiation emitted by the older OB1a and 1b subgroups. However, within the last few Myr, UV radiation from the the OB1c subgroup near the Sword may have exerted a stronger influence. The influence of this younger group is especially evident in the shapes of the L1515/L1516 cloud located north of IC 2118, and in the L1634 cloud located about 3° due west of Orion's Sword. The expanding wind of tenuous plasma that is responsible for inflating the Orion-Eridanus bubble may also have contributed to the shaping of the cometary clouds in its interior.

The distribution of young stars in these cometary clouds indicate that star formation has propagated from east-to-west. Unobscured classical and weak-line T Tauri stars are found predominantly east of the ionization fronts that line the eastern rims of these clouds. Younger, embedded YSOs that are seen mostly at infrared wavelengths and which drive outflows, tend to be located to the west of these ionization fronts.

Figure 14 shows a ^{13}CO image of the Orion A and B clouds illustrating the cometary morphology and velocity gradient in Orion A, and the complex structure of Orion B. Figure 15 shows a cartoon illustrating the relationships between the CO clouds, the Orion/Eridanus bubble as traced by $\text{H}\alpha$, the 21 cm HI emission, and ridges of warm dust emission, and the cometary clouds identified in the IRAS infrared images.

The structure of the interstellar medium in the Orion/Eridanus bubble provides evidence that the energy released by high mass stars has profoundly altered the morphology, structure, and kinematics of the gas in this region. Over the past 5 to 10 Myr, a 20° by 40° diameter bubble has been inflated by the OB association. $H\alpha$ emission traces the location of the current ionization front of the Orion complex. This low density gas is expanding with a mean velocity of about 10 to 60 km s^{-1} towards high Galactic latitudes and towards us. This gas can be seen in absorption against Orion's bright stars, especially in the UV. A tenuous and hot plasma, visible in soft X-rays and in UV resonance lines, fills the bubble interior and the the near-side of the bubble may be as close as 180 pc from the Sun. The western portion of the Orion / Eridanus bubble has been detected in the 1.8 MeV gamma-ray line produced by decays of the short-lived ($t_{1/2} \approx 0.7$ Myr) species ^{26}Al (Diehl et al. 2004 – see Figure 11). Figure 12 shows the apparent geometry of the Orion / Eridanus bubble.

A larger shell of 21 cm HI emission and dust traced by IRAS and COBE data lies outside the $H\alpha$ emission region. The remnants of the giant molecular cloud from which the older association stars formed have been overrun by the expanding superbubble and were accelerated and compressed. The parts of this cloud that lie close to the OB association have higher radial velocities than the gas located farther out. This trend may indicate that the molecular cloud lies behind the superbubble and the majority of the Orion OB association's stars. Apparently star formation occurred preferentially on the near side of the cloud and the resulting release of energy has pushed the surviving cloud remnants away from us. In addition to the Orion A and B GMCs, nearly a hundred smaller clouds are strewn throughout the interior of the Orion/Eridanus bubble and most of these cometary clouds point back towards the Orion OB association. All are visible in the IRAS data, most have bright skins of $H\alpha$ emission, and many emit in the CO lines. The cometary CO clouds have slower velocities away from OB association than the $H\alpha$ or 21 cm HI shell, but larger speeds than the Orion A and B clouds. While some small clouds may have condensed from the expanding supershell as it evolves towards blow-out at high Galactic latitudes and becomes unstable to Rayleigh-Taylor instabilities, the larger clouds are probably accelerated remnants of the proto-Orion GMC.

5. The Origin of Orion's Brightest Stars

Where did Orion's luminaries, Betelgeuse (α Ori; M2Iab) and Rigel (β Ori; B8Iab), and the 2nd magnitude Saiph (κ Ori; B0Iab) originate? The fourth star in Orion's rectangular shape, Bellatrix (γ Ori; B2III) in the northwest corner of Orion, is located only 75 pc from the Sun, and is presumably unrelated to Orion.

Betelgeuse has been estimated to lie 131 ± 30 pc from the Sun based on Hipparcos measurements (Perryman et al. 1997). However, it is a supergiant with a pulsating atmosphere which makes parallax estimation difficult, especially at visual wavelengths below the peak of the Planck function where slight photospheric temperature variations can shift the photo-center. A recent VLA-based distance estimate which is based on the photo-center in the Rayleigh-Jeans limit, places it at a greater distance of 197 ± 45 pc from the Sun (Harper, Brown, & Guinan 2008), about 200 pc in front of the Orion Nebula.

Betelgeuse is a moderate-velocity run-away star with a proper motion of $(\mu_{\alpha\cos(\delta)}, \mu_{\delta}) = [23.98 \pm 1, 10.07 \pm 1.15]$ mas / yr (Boboltz et al. 2007) which indicates motion

towards the northeast at $PA = 68^\circ$, directly towards the Galactic plane. An infrared bow shock precedes the motion of this star (Noriega-Crespo et al. 1997). The heliocentric radial velocity of Betelgeuse is $V_r = 21.0 \text{ km s}^{-1}$. This is 7 km s^{-1} lower than the radial velocity of the stars in the Orion Nebula, 10 km s^{-1} lower than the majority of stars in the Orion OB1a subgroup, and comparable to the 25 Ori stellar aggregate in the 1a subgroup. The new distance led Harper et al. (2008) to re-determine the current mass ($17 M_\odot$) and birth mass ($20 M_\odot$) of Betelgeuse, implying that this star had a main-sequence lifetime of about 10 Myr, comparable to the ages of stars in the OB1a subgroup. However, the 3D motion of Betelgeuse propagated back in time is inconsistent with a direct ejection from this group.

From the proper motions of α Ori ($[24,10] \text{ mas/yr} = 0.026''/\text{yr}$) and the angular separation of α Ori and 25 Ori, the B1 star in the 25 Ori group in Ori OB1a that is about 9.4 degrees from Betelgeuse on the sky, these two stars were closest to each other about 1.3 Myr ago (assuming that the proper motion of 25 Ori is negligible). The radial velocity difference between Betelgeuse and the 1a subgroup of Ori OB1 (excluding the 25 Ori group, which has a radial velocity identical to Betelgeuse) is 10 km/s. To cover the 130 pc difference between the distances of Betelgeuse and the 1a subgroup would require 13 Myr - very different from the 1.3 Myr obtained from the proper motions alone. Betelgeuse and the OB1a subgroup could not have been at the same location at any time.

The main sequence life-time of 10 Myr places a severe constraint on the point of origin of Betelgeuse. If its current proper motion was imparted at birth, Betelgeuse would have been born far above the Galactic plane. Thus, its velocity can not have originated at birth. Either, Betelgeuse was born in an unknown group located southwest of the Orion OB1 subgroups, or if it was born in OB1a, as suggested by its age, it must have gotten two velocity kicks; an initial kick that moved it from its birth-place in OB1a to within about 200 pc from the Sun, and a second kick about 1 to 2 Myr ago that generated its current proper motion.

β Ori (Rigel) has a distance of about $245 \pm 45 \text{ pc}$, similar to Betelgeuse and the IC 2118 cloud and its population of T Tauri stars that is externally illuminated by Rigel. The radial velocity (Kharchenko et al. 2007) is $V_r = 18.8$ to 20.3 km s^{-1} and proper motion is $[1.87, -0.56] \text{ mas/yr}$ (Hog et al. 2000). Thus, there is evidence for foreground star formation about 200 to 300 pc from us, well in front of Ori OB1. Could Betelgeuse have been ejected from this group, perhaps by a companion that exploded?

Alternatively, the OB1a subgroup might have dynamically ejected a massive binary roughly toward the Sun about 10 Myr ago. At $V = 10$ to 15 km/s , it would have moved about 100 to 150 pc towards us. If this binary consisted of Betelgeuse and a more massive star, the massive companion could have exploded in a supernova event about 1 to 2 Myr ago - this constraint arising from the requirement that Betelgeuse be within about 15 degrees of its current location when it got its present motion. The explosion would have converted the orbital motion of the Betelgeuse into linear motion, setting it on its current path. The site of such a supernova explosion would have occurred somewhere between Orion OB1a and the Eridanus Loop. A supernova at this location may explain several aspects of the Orion / Eridanus superbubble such as the extension toward the Sun shown in Figure 12, the location of the near wall (the Eridanus Loop) at a distance of only 180 pc from the Sun, the presence of soft X-ray and 1.8 MeV γ -rays from the decay of live ^{26}Al .

κ Ori (Saiph), the bright star located at the southeastern corner of Orion, also has a distance of about 220 ± 45 pc, and a radial velocity $V_r = 21 \text{ km s}^{-1}$ similar to Rigel. Thus, this star also provides further evidence for recent star formation in front of Orion. There is some circumstantial evidence that this star is illuminating the southern end of the Orion A cloud. Figure 8 shows a $100 \mu\text{m}$ IRAS view of the Orion region. A ring of dust is seen to wrap around κ Ori, (located near the bottom of Figure 8). CO emission associated with this ring blends smoothly into the southern end of the Orion A cloud, raising the possibility that the extreme southern portion of L1641 is much closer to the Sun than the Orion Nebula. Perhaps the L1641 portion of the Orion A cloud is a long finger that is elongated along our line-of-sight.

6. Lessons Learned from Orion

What have studies of Orion taught us? Observations of Orion have yielded the discovery of the first IR-nebula (the Ney-Allen nebula), the first IR-only star (the Becklin-Neugebauer - BN object), the first OH and H₂O masers, the discovery of interstellar CO and many other molecules, the recognition that stars form from giant molecular clouds, the first protostellar outflow, and the first direct visual wavelength images of circumstellar disks (proplyds).

Much of our current understanding of star formation has emerged from studies of Orion:

- Molecular clouds are filamentary, chaotic, and exhibit supersonic internal turbulent motions. It remains unclear if on a large (GMC) scale they are bound by self-gravity and long-lived (survive for many crossing times), or dominated by motions imparted by surrounding flows and short-lived (about a crossing time).
- Stars form from dense cores embedded in molecular clouds. Most star forming cores are located on the sides of clouds that face the center of the OB association. Cores fragment into sub-cores to form groups containing from a few to thousands of stars. Star formation propagates through the complex at nearly the sound speed in ionized gas. In Orion, the 10 Myr old sub-groups are separated from the currently forming sub-groups by about 50 pc.
- Most forming stars are surrounded by accretion disks and power collimated winds and jets that inject energy and momentum into the host cloud. Some massive stars power explosive, poorly collimated outflows (e.g. OMC1).
- The initial mass function is universal, independent of the degree of clustering or other environmental properties.
- Most stars form in short-lived, transient clusters that dissolve in a few Myr to populate the field. The clusters and the cores from which they form exhibit a hierarchy of structure. OB associations consist of sub-groups, clusters, and sub-clusters with no preferred scale.
- Massive stars sculpt the ISM in their vicinity. They create superbubbles hundreds of parsecs in diameter and their energy and momentum injection (UV, winds, SN) dominates the evolution of star forming regions.
- Massive stars form in the densest and most massive clusters, and appear to be born near the cluster center. The Trapezium in the Orion Nebula is a mass-segregated sub-cluster.
- Stellar multiplicity increases with mass. Run-away stars are common among massive stars. While some massive stars were ejected when a more massive companion

exploded, others were ejected by dynamical decay of dense sub-clusters soon after formation.

- The formation time-scale for individual stars is about 10^5 years, for clusters about 10^6 years, and for entire OB associations about 10^7 years.
- The star formation efficiency, averaged over an entire OB association, is about $\eta \approx 1$ to 5%.

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