Riding with the Valkyries

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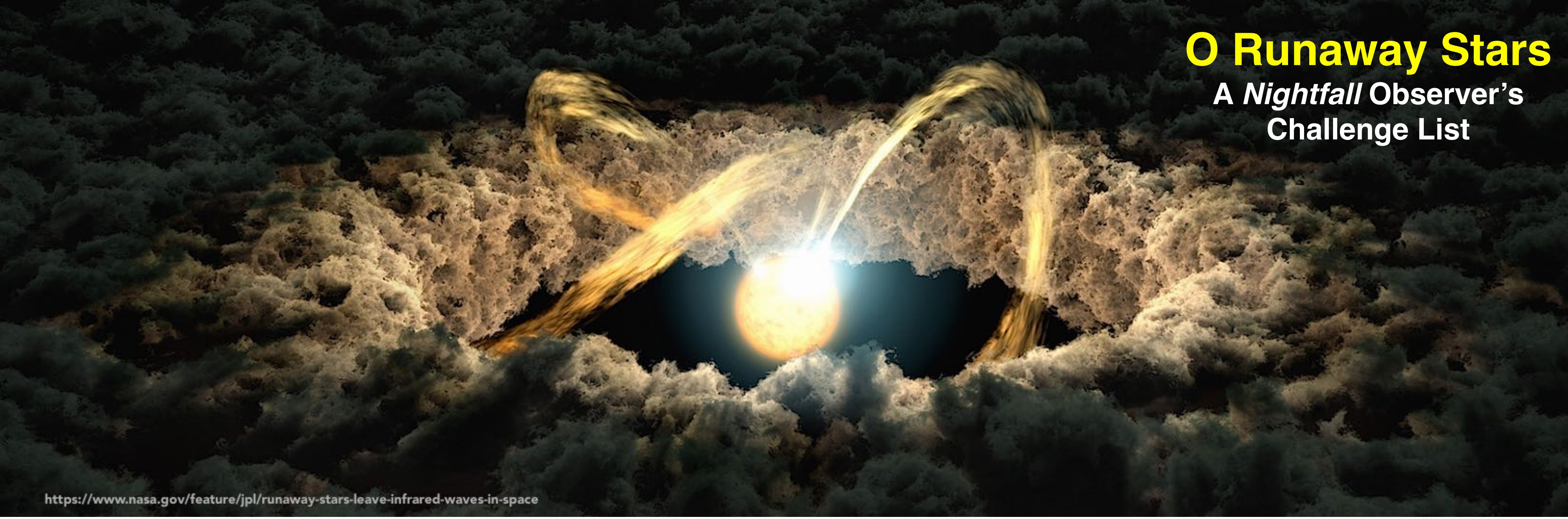
O Runaway Stars
A *Nightfall* Observer's Challenge List



Zeta Ophiuchi is traveling through the galaxy faster than our sun, at 24 km.sec (54,000 mph) relative to its surroundings.

Who doesn't want something new to look at?

Our usual instinct is to go for objects faint and far away. But there is an observing challenge sitting before our very eyes which we haven't paid much attention to: O runaway stars. These are giant, furiously hot Class-O stars, unaccountably speeding along in near-solitude in parts of the Galaxy where they shouldn't be. They are easy to find, bright even in a pair of binoculars. They also tell a tale about stellar life styles within galaxies that we could discover no other way.

The oddities of high-velocity O stars have led some astronomers into some physically improbable dead-ends of surmise, the pursuit of which cost them considerable time, argument, and reputation, only to be vindicated by today's most advanced detection and analytical capabilities. O runaway stars may be an allegory for our belief that truth is what we insist it is.

Why should we even bother with them? They are big, bright, obvious. We can see the ones listed in *Table 1* at the end of this article, either naked eye or using inexpensive binoculars. So why the fuss? What kind of physics could we possibly learn with a pair of binoculars?

Let's take an oft-told example: The stars AE Aurigae and Mu Columbae are flying directly away from each other at velocities of over 100 km/sec each. By compare, the Sun moves through the local medium of the Milky Way at only about 20 km/sec. Tracing the two stars' motions backward to their origin, astronomers end up in the Orion Nebula about 2 million years ago. (Barnard's Loop is believed to be the remnant of the supernova that launched the other stars.)

An O Primer

Let's begin with what is an O star, then why it left the nest to become a field star or runaway, and finally what it's going to do for the rest of its days.

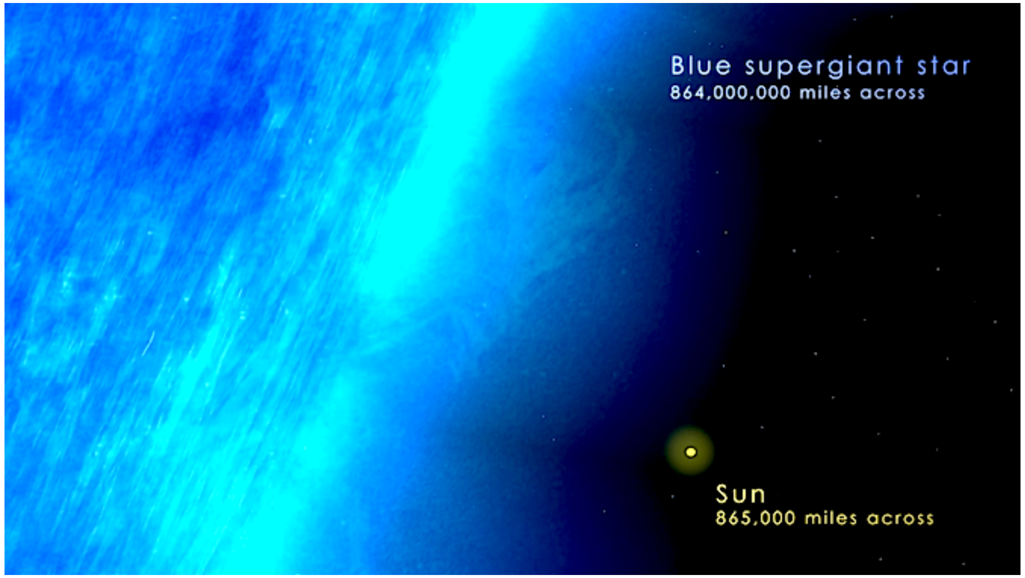
At least 634 O stars in the MW disc are considered "detached," meaning they don't appear to be associated with another object such as a star cluster.

There are many many more in our Galaxy, but the 634 catalogued examples mark the detection limit of the equipment we have today. For stars as bright as O stars, 500,000 to 1.2 million times that of the Sun, the extinction limit along the Galactic disc is roughly 6500 light years (lyr) in the M_v visual band. Our lines of sight along the disc are significantly affected by dust extinctions up to 10 visual magnitudes. *(1, 2, 3, 4.)* The ***O star table*** at the end of this report lists 45 that can be seen from Earth either naked eye or in binoculars.

Massive stars are defined as stars with initial masses larger than 8 solar masses, $M_{\odot}$. They have short lives — 4 to 20 Myr — and explode as core-collapse supernovae. They change appearance and size while traversing various phases of their evolution. Born as O and early B stars, they become blue supergiants. Rigel is a blue supergiant O star, shining 117,000 time brighter than the Sun.

The most massive O stars enter the unstable phase of luminous blue variables (LBV). This class is rare, only about 20 are known; a famous one is Eta Carinae. Other O stars of various mass levels evolve into yellow hypergiants, Wolf-Rayet stars, or red supergiants before they expire in the titanic death throes of a supernova.

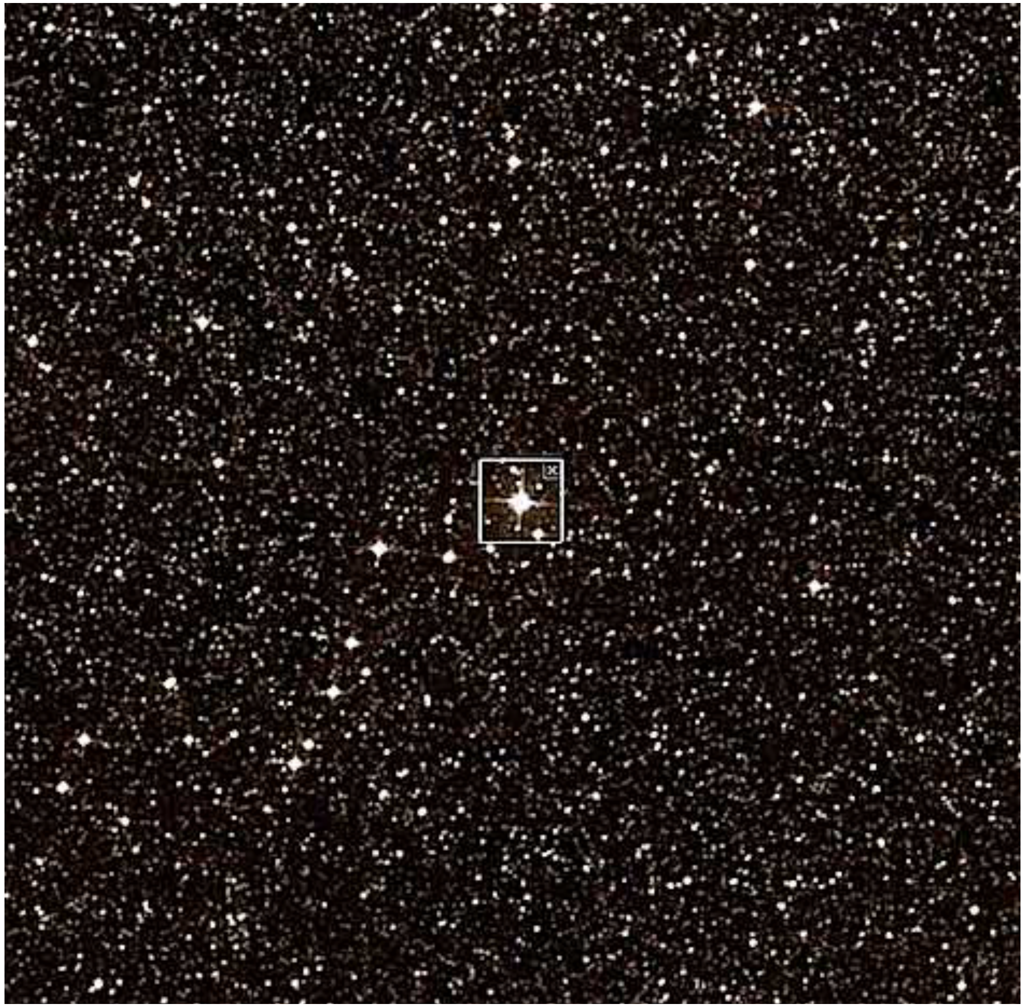
Blue supergiants play a critical role in the origins of life as we experience it. They seed their galactic garden with enormous amounts of alpha-process elements C, O, Ne, Mg, Si, S, and Ca. Any of these elements can synthesise the next heavier element (i.e., to the right on the Periodic Table) by capturing a helium nucleus or alpha particle, a reaction called alpha capture. Helium nuclei exist in great numbers in the cores of stars, but once outside the heat and density of a star core, the nuclei quickly capture free electrons to become atoms or ions. Moreover, O stars supply future star generations with heavy elements such as technetium, barium, strontium, yttrium, and even lead by convectively dredging heavy atoms up from the fusion furnace of the star's core where those elements are forged.



Two Make a Tango, Three Make a Tangle, Four Make a Mess

A concert pianist will tell you that Mozart is the easiest composer for a child to learn but the most difficult for a master to play. O field & runaway stars tell us the same thing. A youngster suitably equipped with a good set of charts could find many in *Table 1*. To professional astronomers those bright, intensely blue wandering pinpoints conceal perplexities that once seemed fairly straightforward, but have been revealed as far more complex by recent observations and calculations.

A few examples: Why do the most massive star clusters produce the most massive binaries? These objects dominate all other populations in the cluster, 50% to 70% of the cluster's most massive stars. Why do ~20% of them get ejected from the cluster before the cluster is a million years old? Why do small handful of supermassive O stars wander the far meridians of the Galactic reach so slowly they cannot be back-traced to a home cluster?



HD 091452 in Carina. See De Bruijne, J.H.J, & Ehlers 2012, Radial velocities for the HIPPARCOS-Gaia Hundred-Thousand-Proper-Motion project, A&A 546A, 61-61 (2012). Image courtesy of WikiSky.

Twelve years ago slow-movers like HD 091452 to the left inspired a team of astronomers (*1, 2*) to suggest that the only explanation for their solitude is that they were born as O stars *in situ* (in place) not far from where they are now. The term *in situ* implied that a very massive star formed all by itself in the middle of nowhere in what the team referred to as "one-star clusters". The implication that a ±50 $M_{\odot}$ star was somehow born in near-emptiness bearing no clues to its origins. The reaction was quick and caustic: "*Wh-a-a-t?* No gas clouds? No dust? No companion stars? *Balderdash!*"

Unfortunately for the critics, the de Wit paper was one of many published after a 2005 conference in Grenoble, *Massive Star Birth: A Crossroads of Astrophysics*, sponsored by the International Astronomical Union. (The IAU is a clearing house for international astronomy conferences.) Reading the many papers produced at that conference reveals that the *in situ* idea was advanced as a possibility and not a conjecture. Much of the negative reaction to the idea that a 25 $M_{\odot}$ star can be born all by itself was based on perception rather than a close read; moreover, most of the critics hadn't attended the conference.

The first decade of this century was a time in which one school of star cluster formation held fast to the assumption that molecular clouds are near-spheres when they enter into a spiral arm and that subsequent collapse due to shear effects takes place in a gravitationally spherical environment that gets twisted and then fragmented by torque.

The second school opined that the complex mix of forces that act on a molecular cloud were too powerful, ubiquitous, and unpredictable for any single-cause formation theory to prevail universally. Cloud collapse trends toward filamentary and clotted structures in which cluster formation occurs in multiple regions spanning millions of years, each of which significantly impacts the others. (The Lagoon Nebula, M8, is an excellent example of this broad brush painting near-chaos; see the image parsed on pages 1 & 2 of this month's *ASSA Nightfall.)* Watch it happen here.

These forces greet an innocent, pure, gas sphere like an an unschooled youth arriving at a bus station in a colossal, inhospitable city:

- torque
- shear
- tremulous high-Mach* turbulent shocks
- acting violently but on small scales
- broad density waves advancing outward from nearby star cluster gas expulsion phases
- nova and supernova blast waves
- pencil-thin polar jets from large stars undergoing initial collapse in the protostar stage; these jets are enormously corrosive to things they hit
- multiple interacting magnetic fields caused by events as diverse as cosmic ray outflow from colliding-wind binaries and cloud-scale flux tubes as the clouds flatten into other gas clouds nearby

* The term *supersonic* means that the velocity of a moving object is greater than that of the velocity of sound in the surrounding medium. While it is about 343 m/sec in the Earth's lower atmosphere, it is about 10 km/sec in the nearly empty interstellar space. Only when gas bodies traveling at supersonic velocities with respect to their medium slow to subsonic speeds can the forces of magnetic fields and gravitation act on the cloud, leading to free-fall collapse and, if there is sufficient mass, cluster formation.

The list goes on. Star formation occurs under anisotropic, stringy, clumpy, unpredictable conditions with multiple rates of change occurring concurrently throughout the cloud. It's an unholy mess.

The author W. J. de Wit added plenty of caveats for uncertainty. However, more fastidious astronomers (a category which includes quite a number of them) took exception to the very idea and published rebuttals (*1*, *2*). Some merely tut-tutted, others patronised (*3*).

Today that teapot tempest was long ago and far away. We enthusiasts with a pair of binoculars can chase O stars to our heart's content. Bright as they are in *Table 1* (M_V 2.7 to 10.1), we see only a few percent of the total radiation these stars produce. Most O star radiation is emitted as ultraviolet (UV), which is beyond our visual range. We bino-bearing budding *Mozartistes* learning about the sky's bounty are rewarded in two ways: First, O stars are uncommon and unusual objects to start with. Second, they are so easily detected that we can spend many inspiring evenings under the stars armed only with a good star chart or cellphone app.

Unbound O stars in the Milky Way and other galaxies are often called "*O runaways*". The exact definitions are rather more strict. True runaways are defined as having space velocities of >40 km/sec (some argue for >30 km/sec). High-velocity runaways are fairly easy to trace backwards to the birthplace, even though they might be hundreds of light years away. Either they were ejected from their parent cluster by dynamical interactions, or they were a binary system in which one of the pair exploded in a supernova. It's not all that difficult to become a runaway — the escape velocity from a 10,000 $M_\odot$ cluster's potential well is roughly 6.5 km/sec, while ejection velocities easily attain 40 km/sec up to hundreds of km/sec.

O B A Wandering Star

Four mechanisms can give rise to an O runaway star:

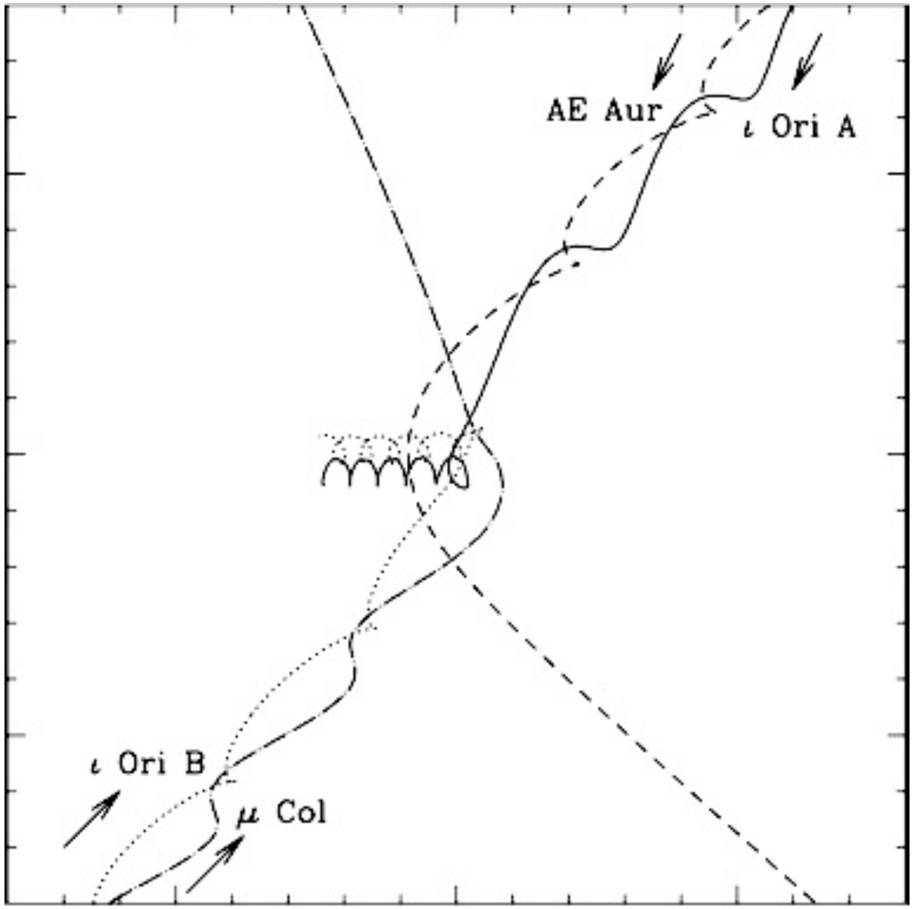
- **A close encounter between two massive binary systems** may result in the disruption of both systems. Two of the four stars are ejected at high velocities in opposite directions from each other. The other two form a new binary. The oft-cited duo Mu Columbae and

AE Aurigae both originated in a binary-binary ejection near M42.

- **A close encounter between a binary and a star more massive** than the binary's individual stars results in the binary being split apart, the least-massive star being ejected at moderate velocity, and the remaining stars forming a new binary with a wide elliptical orbit. The binary NGC 3603-A1 is an example (see linked article § 4).

- **A three-way encounter** between a massive binary and a less massive star ends up with the binary losing about 40% of its orbital energy. The energy accrues to the third star by angular momentum transfer, propelling it off on a high-speed journey at right angles to the centreline that connected the two systems. This mechanism is is referred to as dynamic ejection. Two scenarios can result. In the first, all three stars can merge into a supermassive, very short-lived star of the blue-straggler type. In the second scenario, two very massive stars of >60 $M_{\odot}$ each interact with a star even more massive, ejecting a wandering binary. If this happens in the centre of a very massive cluster, the wanderer can be accelerated to a disproportionately high velocity considering the masses involved. The 83 $M_{\odot}$ and 82 $M_{\odot}$ binary WR20a presently moving away from the 2-million-year-old, 15,000 $M_{\odot}$ cluster Westerlund 2 at 65 km/sec. (Wd 2 is the cover image on this article.)

- **In a binary supernova**, one of the two stars in a massive binary goes supernova before the other. The surviving member gets double-whammy energy injection — first, a massive shove from the detonation itself; second, when when the surviving star's angular momentum suddenly shifts from a circle to a line. The directional shift is immediate. The shock wave arrives later, depending on how far apart the stars were. It becomes a glancing blow that kicks the



Mu Col and AE Aur scattered off the massive binary Iota Orionis to become high-velocity runaways. This image shows only a small portion of the core of the cluster, where the orbits crossed paths and then scattered. Source, Gaulandris & Portegies Zwart 2004.

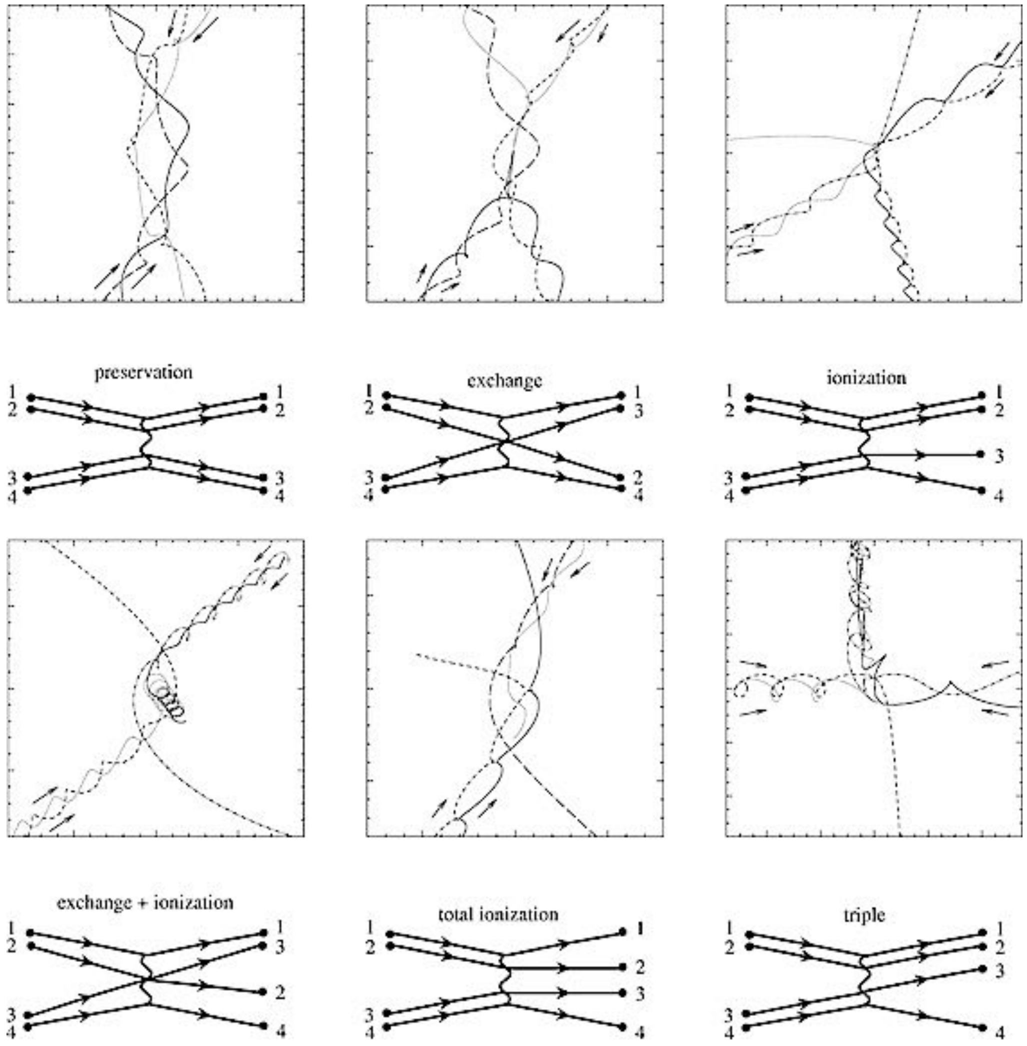
star so far off its trace-back path that we cannot deduce where the star originated. The space velocity of the O stars released in this process is the vector sum of the ejection velocity of the binary system, the orbital velocity of the star, and the kick velocity imparted to the star by the supernova remnant, a neutron star or black hole. Your guess is as good as mine where the thing ends up

> A well-known example of a related set of runaway stars is the case of AE Aurigae, 53 Arietis and Mu Columbae, all of which are moving away from each other at velocities of over 100 km/sec. For comparison, the Sun moves through the Milky Way at about 20 km/sec faster than the rotational velocity of the local spiral arm. Back-tracing the AE Aur and Mu Col motions to a common origin, their paths intersect (see high-resolution visualisation here) in the Orion Nebula Trapezium Cluster (p.9) some 2 million years ago.

Rabbit, Run

Isolated massive O stars in the general field population tend to fall into three different categories. These roughly reflect the mass -vs- velocity structure of the original cluster stars.

True runaways hurtle along at velocities of >40 km/sec and are mostly the 40–120 $M_{\odot}$ heavyweights. Table 1 lists all the runaways we can see in a small telescope. They start their lives in a massive star cluster, from which they were ejected in wrangling scrums between a very massive binary and a wandering interloper (which might also be a binary). Commonly, this occurs within the first million or so years during the formation of a 4,600 to 20,000



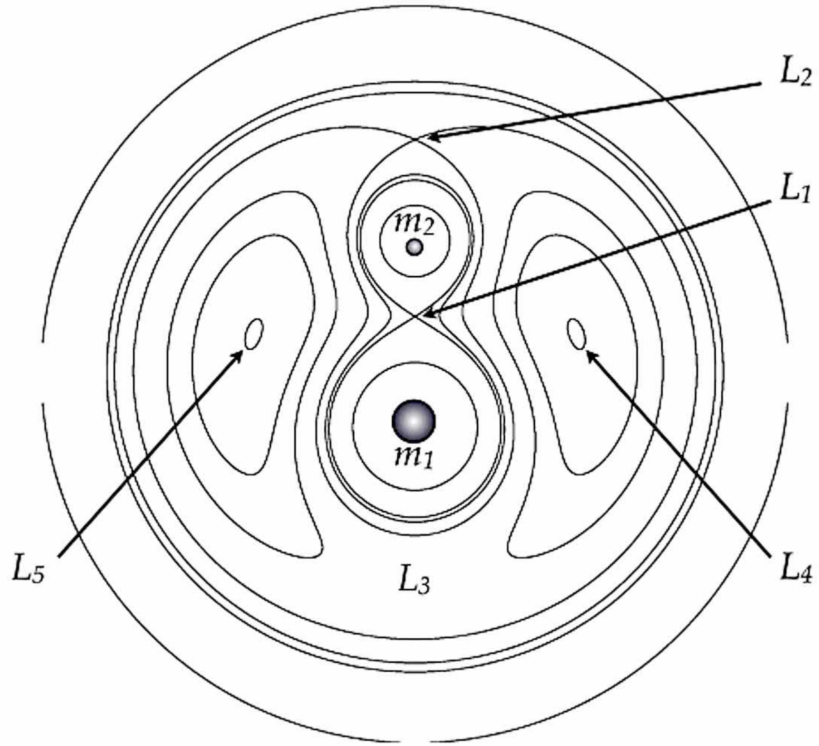
N-body simulations of stars escaping from the Orion nebula. *Source:* See Gualandris, A., Portegies Zwart, S., Eggleton, P.P., 2004, MNRAS v. 350, # 2,615–626, Fig. 2.

$M_{\odot}$ cluster when the cluster contracts so rapidly that astronomers refer to the process as core collapse. See Mark Krumholz's excellent series of video-like simulations of star and cluster formation: 1, initial molecular fragmentation and collapse (edge-on, face-on); 2, stars lighting up & clustering between 134,606 years and 213,752 years after free-fall collapse begins; the stars exiting offscreen are runaways ejected during the earliest stages of cluster formation; 3a, 6-panel sequence of trinary formation, 3b, sim of the same formation.

It's not difficult to become an O runaway, but very difficult to understand how they get that way. In 2011 Michiko Fujii and Simon Portegies Zwart conducted an N-body simulation which began with a pair of 16 solar-mass O stars orbiting around each other in 500 to 1000 days. The team introduced two 16 $M_{\odot}$ stars into the core of the cluster and assigned them ages of 1 to 4 million years. They ran various scenarios within the sim, setting the initial cluster mass, for example, at 2000 up to 4500 $M_{\odot}$. Sims typically compute several dozen to several hundred individual runs so astronomers can assess the interactive effects of all the parameters.

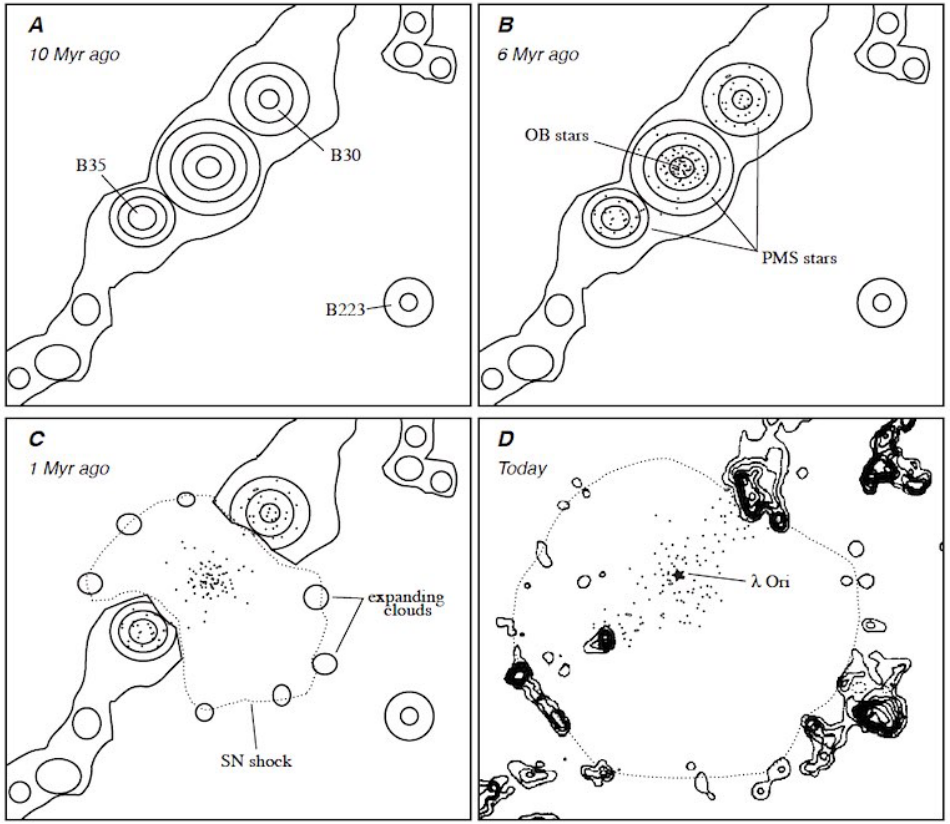
Fujii & Portegies Zwart studied star interactions only, ignoring the enormous mass of the original natal gas cloud that never made it into stars. On average a star cluster only uses up 3% to 5% of the total gas supply of the molecular cloud from which it was made. The rest diffuses back into space to eventually be reused. In most cluster formation, the unused natal gas is blown away within the first couple of million years.

Roughly half the O and B stars in the Fuji & Portegies Zwart *N*-sim were binaries, about average for a mid-sized cluster. One of those core binaries outweighed the rest. It became the dominant force affecting all other stars in the cluster core. In real star clusters there is always one most-massive binary living at the heart of the cluster. The orbits of core binaries are circularised by nonstop interactions with other massive stars, a process called "hardening". Eventually the most massive pair becomes so hard it well earns its sobriquet Bully Binary (BB).



A binary star's dynamical cross-section is the region defined by the outer figure-8 encircling the two stars in this drawing. The inner figure-8, called the Roche Lobe, is almost congruent with the dynamical cross section but a bit smaller. The *Roche Lobe* defines the region within which orbiting material is gravitationally bound to that star. Conversely, the *dynamic cross-section* defines the potential capture radius of stars approaching from outside. L1 through L5 are Lagrangian points where the net gravitational potential of the two large masses nulls out the centripetal force required to orbit with them. See this article by M. J. Benacquista & J. M. B. Downing for comprehensive details of binary star dynamics. Their article is nominally about globular binaries, but binaries in massive young clusters live by many of the same rules. The MODEST web group is a consortium of computation and analytical specialists devoted to modelling the dynamics of multi-star system.

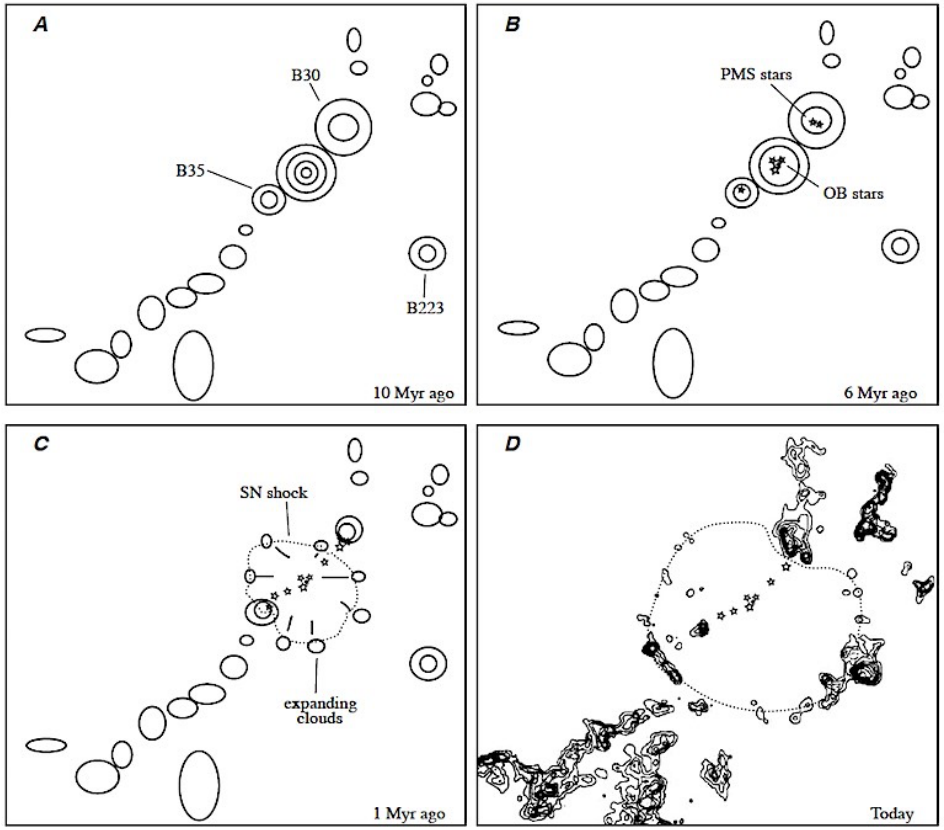
Then Fujii and Portegies Zwart injected a third 16 $M_\odot$ star, aimed directly at the core BB. The three stars entered into a complex lissajous dance whose final thank-you-ma'am was one of the three (usually the lightest) being flung clean out of the cluster at >30 km/sec. The remaining pair lost up to 40% of their binding energy. The lost energy was transferred to the ejectee by the angular momentum. The BB's orbit then shrank and hardened again.



Most star clusters originate in dense filamentary gas threads so often seen in astro-images. The most massive and thus hottest cluster creates a bubble of hot gas that crunches into the cold gas around it, triggering second-generation clusters.

Neighbourhood toughs

Since a cluster's heaviest stars naturally gravitate to the core of the cluster, a resident bully binary will eventually reduce a significant amount of the cluster's overall mass. A BB can eject up to 23 smaller stars before it loses so much binding energy it can't hold itself together any longer. It then either self-ejects as a wandering binary, or melts into the cluster's general



Very compact high-mass gas clouds collapse into clusters of high-mass O and B stars which radiate enormous amounts of UV radiation. This initiates a rapid gas-clearing shock wave. Supernovae compress the ring into arcs of clusters.

population. But by then the BB's havoc has devastated the cluster. It loses so much stellar mass in the core that it can no longer retain all its small-fry stars (like our Sun) out in the halo. The lightweight stars diffuse into the galaxy's disc, first as a moving group, then an association, and finally footloose and fancy-free (like our Sun).

There's a local angle to all this. The Sun once belonged to a star cluster of about 4,000 $M_{\odot}$. Today, after considerable effort and pricey computer time, astronomer's have found exactly one star out of those several thousand Solar siblings — the star F Hercules. You can spot it in a pair of binoculars.

The M_V 6.8 star HD124314 in Centaurus is a post-supernova binary (not a single star as is usually the case) that was turned from a typical fast-mover to a slowpoke. The pair were ejected along with a more massive single star as a trinary. When the massive star detonated into a supernova, the smaller star's velocity was reduced by the kick of the supernova explosion and redirected into a different, untraceable vector.

The orbital diameters and differing masses of a bully binary play a significant role in how many stars it will eject, how frequently, and for how long. The region in which a BB can be destructive is called its orbital cross-section. The most prolific type of binary producing massive runaways are supermassive stars in the central core with relatively wide orbits between 1000 and 10,000 AU (astronomical units). A long-radius orbit has a greater cross-section within which to interact, but its effective energy density E_{eff} weakens with distance.

Binaries are produced naturally by the cluster formation process, or more accurately the kinetic heating effect of gravitational collapse. Once a binary enters the centre of the cluster, it hardens by ejecting hapless interlopers, becoming more circular, less elliptical, and therefore more impenetrable, or "hard". A hardening binary in turn hardens the cluster's core by more efficiently ejecting the cluster's most massive stars and circularising the orbits of the other stars. A cluster core density of 47,000 $M_{\odot}$ per cubic parsec (34.6 cubic light years) is typical for a cluster after its first core collapse. You can view the dynamics of star cluster core collapse in this 3-D ESO sim.

Core collapse has the unintended consequence of rendering the cluster gravitationally weaker. Low-mass stars evaporate from the halo through the funnels of the L1 and L3 Lagrange points. This in turn induces core to contract ever further, again and again, in a fruitless attempt to achieve gravitational balance. It's like entering a casino with a fat wallet: every time you spin the roulette, your wallet gets thinner. There's a limit to just how many stars a bully binary can eject before its own orbit and potential (gravitational well) are weakened. Since energy is never destroyed, the binary's binding energy (angular momentum) adds to the kinetic energy (velocity) of the ejected star; that's where ejected stars get their whizz. For more information about *N*-body sims, see *1, 2, 3*.

Massive binaries with very short periods <10 days have such small gravitational cross-sections that most never undergo a dynamical energy exchange with another cluster member. Such binaries are considered primordial and likely to remain bound for their entire lives. Only a very strong interaction with a high-mass star can cause a merger of all three stars into a blue straggler. Stars can merge if their orbits become smaller than the stars' Roche limits. They begin to exchange envelope mass via their Roche Lobes, until so much has exchanged their cores finally melt into each other as blue stragglers. By the time the exchange is complete the stars have ejected a considerable proportion of their mass; their combined masses are, on average, 70–80% of their mass as a pair. See *1, 2, 3*.

There is a less-common class of blue straggler called yellow straddlers. These originate when the binary comprises one large massive star that has gravitationally captured a second much smaller star. If they eventually merge, they do not continue up the main sequence like blue stragglers, but rather burn longer at the same temperature and luminosity — that is, they rise straight up by 0.7 magnitude on their colour-magnitude diagram before hydrogen flame-out initiates the long haul up into the red giant phase.

Relatively wide and massive binaries whose orbital periods are ±1000 days are the most efficient at ejecting stars from the cluster. Between 25% & 35% of O stars are ejected from very young clusters <1 Myr. The mass loss is greatest if the cluster was highly concentrated at the time of its free-fall collapse. Since a cluster generates one runaway-producing Bully Binary during each core collapse, the relative fraction of runaways is inversely proportional to the mass of the cluster. Massive star ejection begins before its gas ejection phase, between 300,000 and two million years.

A star cluster loses a considerable proportion of its mass when its O stars are ejected. Typically the mass loss is 60–80% of the cluster's initial mass during the first 260 Myr of its evolution. Around half that occurs in the first 5 to 10 million years when its first hot young stars eject the cluster's natal gas, the portion of the original cloud that wasn't consumed during star formation.

Gas-clearing is not the only mass loss a star cluster endures in its youth. Dynamical loss includes stars ejected in binary encounters as described above and supernovae ejecta. Additional mass loss occurs from the stars' fusion processes, i.e., atoms and ions hurled out by the star's hot surface radiation. Even more mass is lost to dynamical evaporation as individual stars wreak havoc on each other during random-walk interactions. When the cluster core collapses its larger stars sink toward the centre, allowing the low-mass stars in the halo to drift away from the outskirts into the galaxy as a whole.

Those stars just don't wander off willy-nilly. Their orbital vector must be aimed at one of the cluster's Lagrangian Points, L1 or L3, and also exceeding the escape velocity from the cluster's potential well. This is a rare occasion where you can escape the clutches of the law by exceeding the speed limit. ("Officer, I was just obeying the Virial Theorem. Mr. Clausius said I could." You've got problems if the officer replies, "Sir, the law says $1/2\ mv^2$ and you were going more than twice that.")

In the first 10 million years the overall toll on the cluster is fierce. A cluster's half-life — the period in which half the original cluster members are lost — ranges from 150 to 800 million years, depending on the cluster's initial stellar density. More tightly packed clusters persist longer. The Double Cluster in Perseus is about 12.8 Myr old, the Pleiades about 110 Myr old (estimates vary), and at the opposite end of the scale, M67 in Cancer, NGC 6791 in Lyra, and Collinder 261 in Musca are over 6 billion years old. It comes as little surprise when observing the latter three clusters that they look very sparse, dim, and frail. Looks are deceiving. You have to be a pretty tough old buzzard to survive what a galaxy throws at you.

M67 lies at such a high angle from the Galactic plane (31.8°) that it was either stripped from an accreted dwarf galaxy, or it formed from a very massive high-velocity cloud penetrating into the nascent Milky Way from far above or below. (Blanco I in Sculptor is another of these, although it is only a few hundred million years old.)

NGC 6791 likewise lies well above the Galactic plane, but, like Collinder 261 in Musca, it also resides near the Milky Way's co-rotation radius. That is where the rotational velocity of stars circling the galaxy matches the rotational velocity of the spiral density wave. Our Sun likewise resides near the corotation radius, whose tangent vector is 1.06 times the Sun's.

In most cases, the cluster eventually thins into a stream of unbound stars too distant from each other to be a cluster but still a group moving in similar directions at similar speeds.

Bullied stars turn into bullies themselves

Morality isn't quite the same out there in space space as it is down here amid your average church bake sale. Even laze-along O field stars are tough customers. Gas dynamics differs from social dynamics in several ways.

First, stars ejected by multi-star interaction in a cluster are runaways in a very real sense: a 20 or 30 $M_\odot$ star moving at 40 to several hundred km/sec

Lonesome Cowboys

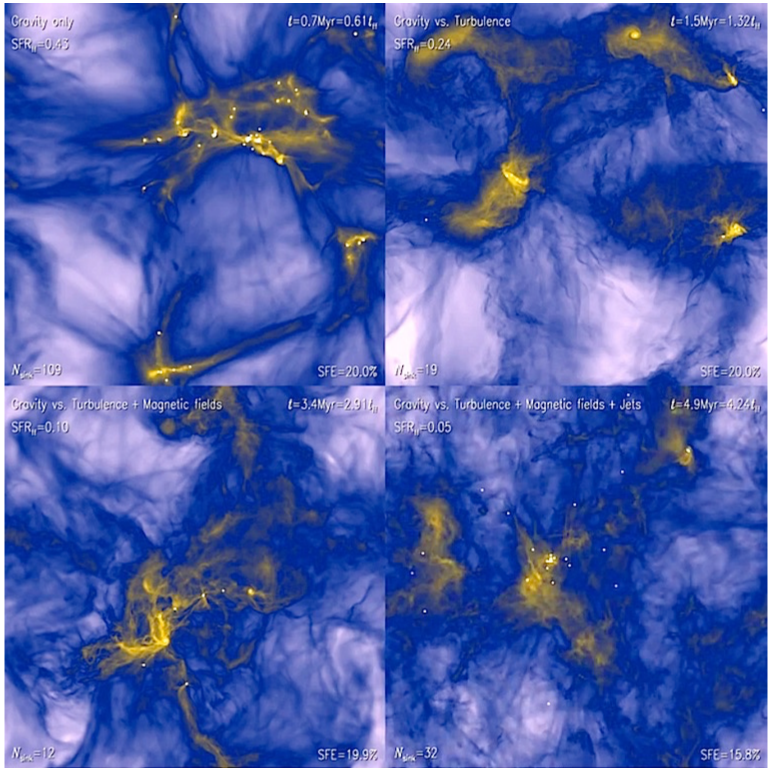
Field runaways are the high-velocity club's more leisurely cousins. They travel between >5 and <40 km/sec. Many can be traced to their birth clusters, but a subclass of them can't be traced to anything.

O stars just passing through would be perfect neighbours — except that they shine at 500,000 to 1.2 million times the intensity of the sun. If one plunked down in place of the Sun, we would be toast before we knew it. The world's oceans would evaporate in a few weeks.

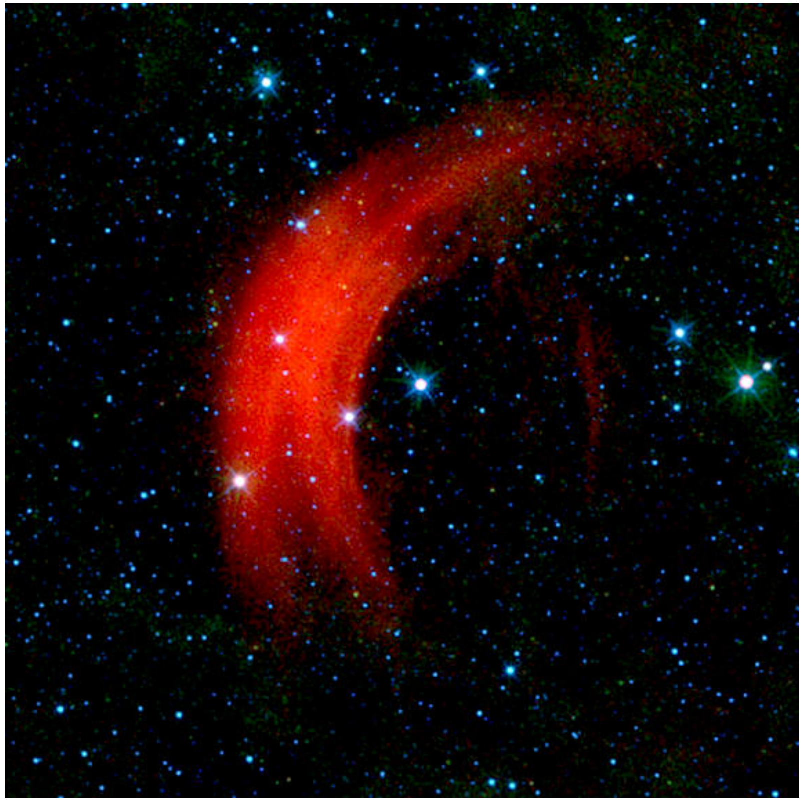
To we backyard observers at our telescopes, high-velocity O stars are almost — but not quite — motionless. If we had, say, a spare century available on our observing schedules, we might note that a few are moving along at a pretty fair clip — 3 or 4 arc seconds per 100 years for the fastest ones in the accompanying table. Theirs is a race where the lithe, limber chaps haven't as keen a chance as the heavyweights.

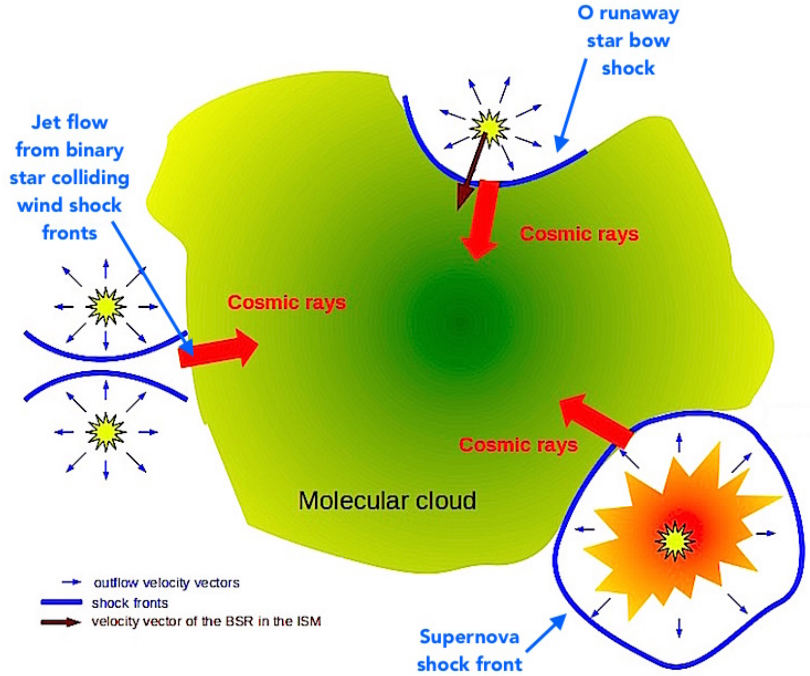
O Solo Mio

***In-situ* field stars** are such slow movers (<10 km/sec) that they are, along our sight lines, not doing much. "*In-situ*" means "in place". They are true O Solo Mio objects that can't be traced to an origin. In the early 2000s a number of astronomers advanced the view that these slow-movers did not travel there, they formed there. This proved unsupportable given the ground-based equipment and limited capability of modelling algorithms available at the time. Many of the wanderers were found to evidence bow wakes, which seemed like a definitive refutation of pre-Hipparcos vector-estimating methods. But today, with millimetre- and micron-band radio telescope arrays like ALMA and Plateau de Bure, plus x-ray telescopes like GALEX and Spitzer in orbit; as well as sophisticated adaptive mesh algorithms, the idea of massive star living and dying alone is being revived. Watch this space.



Interaction of four star-forming forces on a proto cluster. Each force is considered in isolation, then added to the previous ones to show the net effect on the final cluster. *Top L*: gravitation only. *Top R*: Grav. & magnetic fields. *Bot.L*: Grav & magn fields plus turbulence. *Bot.R*: The divisive affects of polar jets on all other influences. From Federrath 2012 & also 2013.





This O runaway is the well-known Alpha Camelopardalis (α Cam), an easy naked-eye runaway. α Cam is moving supersonically at 60–70 km/sec relative to the gas in front of it. Like most shock fronts, Alpha Cam's bow can't be seen in visible light. This WISE IR image reveals its arc of heated gas and dust. The heating isn't caused by the star's high velocity because the gas medium through which a Cam is hurtling is so thin (interstellar gas averages 5 to 10 particles per cm^2). α Cam is an O supergiant that emits a powerful high-velocity wind which in effect multiplies the forward velocity of the star. When α Cam's furiously outflowing wind slams into the interstellar medium, the effect is like the shock wave in front of a supersonic airplane. An arc of superheated gas forms, which we detect in near and IR wavebands.

Large hydrogen clouds pepper interstellar space. Most originate outside a galaxy and are pulled in by gravity. When they enter the galaxy disc plane it is not a friendly place. The disc is rotating, so torque and shear compress and twist the cloud. It is penetrated by a weak but all-pervasive magnetic field that threads the spiral arms. Supernovae blasts compress and heat the cloud along bubble-like shock front. Any wandering O or B supergiants that hurtle through also produce a shock front that shock-heats the cloud. Binary stars radiate energy and particles. Compact, fast rotating, high-mass binaries create colliding-wind fronts which stream jets of high-velocity, high-temperature gas into the cloud like a drill. The cloud is attacked by blast waves of hot gas from star-clusters' gas clearing phase. These forces all act to compress and break up the cloud into filamentary structures and dense lumps. As divisive as these forces are, they are necessary for the cloud to compact in multiple tiny pockets, where gravity can overcome all other forces until the cloud free-falls into a star-forming region. Half a million later the first star cluster is shining.

The Thousand Stings of Withering Linger

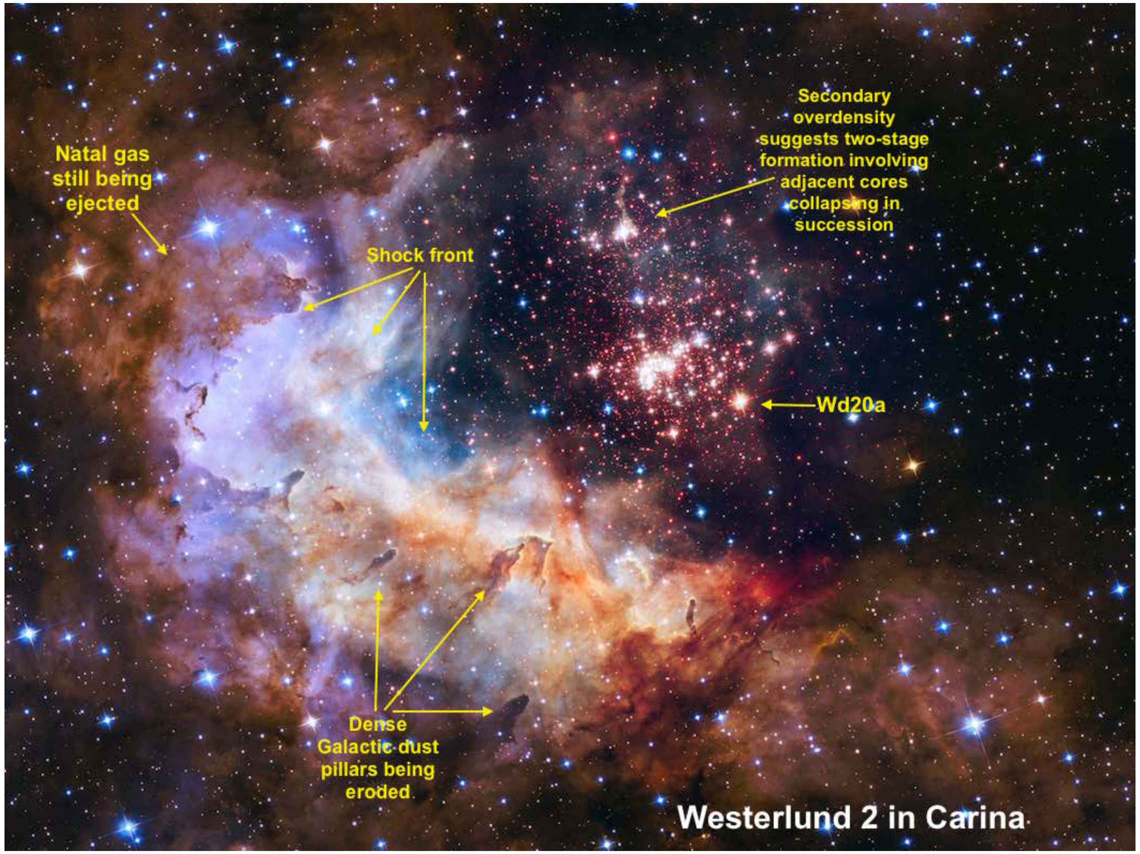
The star cluster Westerlund 2 is >2 million years old and resides in the Gum 29 star-forming overdensity 20,000 light-years away in the Scutum-Carina spiral arm. Wd2's colour-magnitude diagram (CMD) looks more like a ladder than a main sequence. It contains some of the brightest, hottest, most massive stars in our Galaxy. As can be seen in the image, Wd2's birth gas has been cleared entirely from the main body of the cluster, though some remains mixed with one of the multitude of dense gas and dust clumps of the region.

Dense, dusty gas clouds in the Wd2 environs are numerous and severely fragmented. This points to a region undergoing considerable high-velocity turbulent shock fronts from supernovae, magnetic fields, shear and torque forces from the underlying spiral arm, and jets from infant stars ejecting excess accretion matter. Watch all these processes going on at once here.

Astronomers are uncertain whether a second stellar overdensity visible on the image is actually associated with the main Wd2 cluster; the uncertainty is associated with the complex dust extinction structures in the area. The main cluster is reddened by 2.3 $E(B-V)$ photometric magnitudes, while the stellar overdensity N of it is reddened $E(B-V) = 4.7$ magnitudes.

Wd2 is one of the three hottest, densest supermassive young clusters (SSCs) in our Galaxy. The others are Westerlund 1 and NGC 3603. [The Milky Way bulge sports five more super star clusters like Wd2, named Arches, Quintuplet, Central, RSCG1, and RSCG2. These were formed by entirely different galaxy formation physics than the disc SSCs and will be treated in a future *Nightfall* article.]

To the amateur, Westerlund 2 is a difficult object. It is so faint that it looks more like an asterism. The eyepiece impression looks like somebody stomped on the Trapezium. The cluster contains at least a dozen early O stars whose T_{eff} surface temperatures are >38,000 K and more luminous than 230,000 Suns ($L_\odot$). There are 20 older and less luminous O class stars in the cluster, all main sequence objects, plus a very large number of <2.5 $M_\odot$ pre-main sequence stars whose cores have not yet ignited into

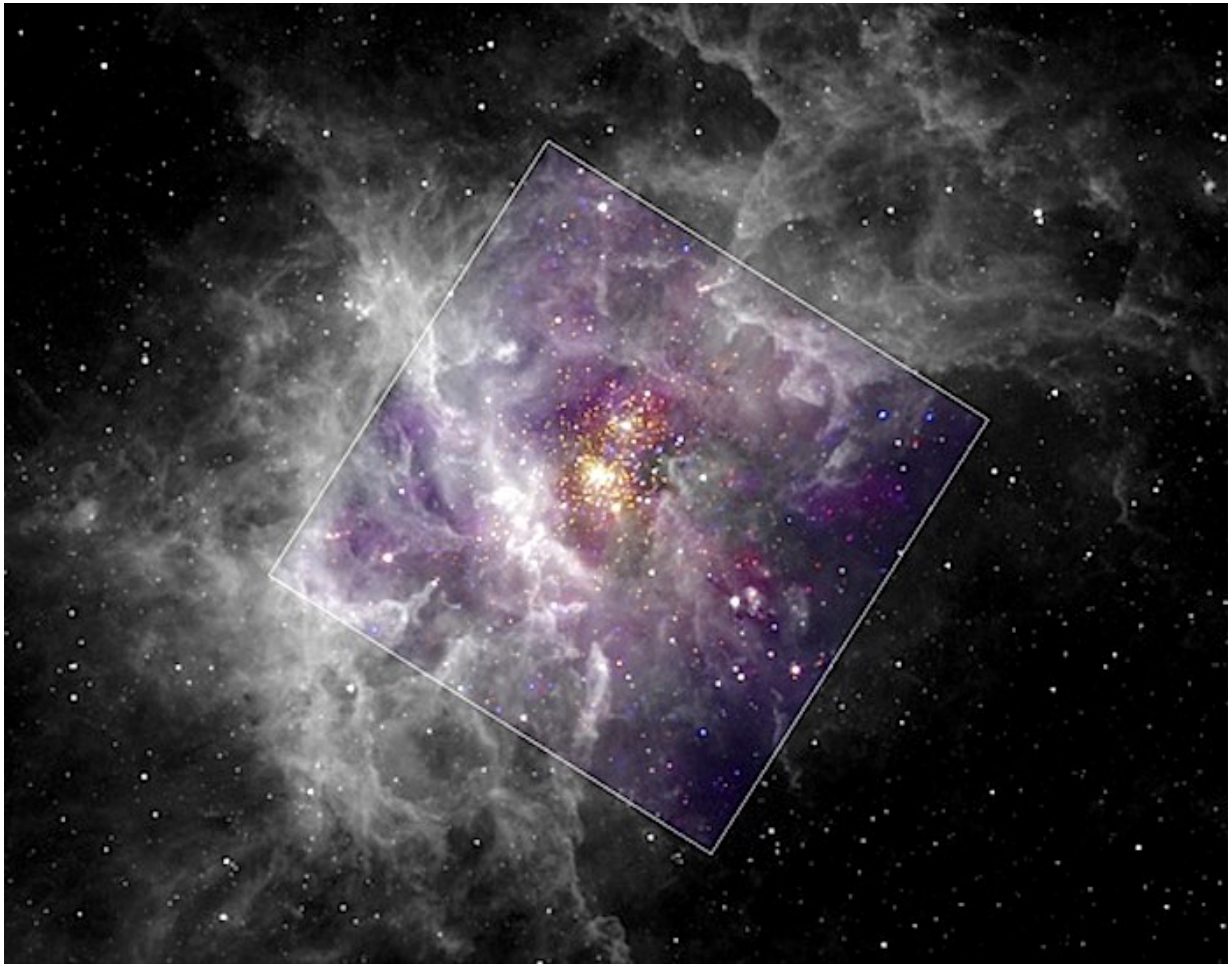


Source: Hubble Space Telescope, STSI.

hydrogen fusion. These latter stars constrain the age of the cluster to ± 2 Myr.

Some of Wd2's progeny are spectacular. Several Wolf–Rayet stars are associated with the cluster, although not in the core. WR20a is a binary of two Wolf-Rayet (WR) stars (which we will look at more closely below),WR20aa, WR20b, and WR20c are all single massive stars whose photometric vectors suggest they are very early runaways from the cluster. The Wolf Rayets are extremely young massive objects of the OIf*/WN spectral types, which makes them amongst the most luminous stars in the Galaxy. Stars of this category are very massive hydrogen-burning stars that are dredging nitrogen and helium to the surface in giant convection bubbles. WRs are very unstable, hurling off violent stellar winds which seed the galactic medium with Nitrogen; WRs are a significant source of this element on Earth.

The image to the right shows Wd2's significant micron-band emission that highlights dust, and far IR emission, which traces thermal densities and therefore gas cloud densities. Now we can clearly see that the secondary overdensity to the N is indeed an associated cluster, likely brought about when a pair of gravitationally associated high-mass gas clouds both initiated free-fall collapse at about the same time. Unfortunately, this region is so riven with differential dust extinction that meaningful conclusions cannot be drawn without more detailed thermal photometric data.



Here we easily notice the effects of differential extinction caused by nonluminous filamentary and pillar-like structures. The paired-cluster appearance of Wd2 is due in good part by a band of dust dividing them. Wd2 has begun to expel its natal gas, but it's no Pleiades yet. Image source: *NASA*, *APOD.*

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Get your gear, mates.

We got riding to do.