

THE ORIGIN OF RUNAWAY STARS

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Received 2000 July 28; accepted 2000 September 1; published 2000 November 16

ABSTRACT

Milliarcsecond astrometry provided by *Hipparcos* and by radio observations makes it possible to retrace the orbits of some of the nearest runaway stars and pulsars to determine their site of origin. The orbits of the runaways AE Aurigae and μ Columbae and of the eccentric binary ι Orionis intersected each other ~ 2.5 Myr ago in the nascent Trapezium cluster, confirming that these runaways were formed in a binary-binary encounter. The path of the runaway star ζ Ophiuchi intersected that of the nearby pulsar PSR J1932+1059, ~ 1 Myr ago, in the young stellar group Upper Scorpius. We propose that this neutron star is the remnant of a supernova that occurred in a binary system that also contained ζ Oph and deduce that the pulsar received a kick velocity of ~ 350 km s $^{-1}$ in the explosion. These two cases provide the first specific kinematic evidence that both mechanisms proposed for the production of runaway stars, the dynamical ejection scenario and the binary-supernova scenario, operate in nature.

Subject headings: astrometry — pulsars: individual (PSR J1932+1059) — stars: early-type — stars: individual (AE Aurigae, ι Orionis, μ Columbae, ζ Ophiuchi)

1. INTRODUCTION

Runaway stars (Blaauw 1961) distinguish themselves from the normal population of early-type stars (spectral type O and B) by their large peculiar velocities (up to 200 km s $^{-1}$) with respect to the mean Galactic rotation and by their isolated locations. About 10%–30% of the O stars and 5%–10% of the B stars are runaways, with the precise fraction depending somewhat on the definitions (Gies 1987; Stone 1991). Since early-type stars are relatively young (a few to ~ 50 Myr old), the distances traveled by the runaways are relatively small (a few hundred parsecs to a few kiloparsecs), and it is therefore possible, in some cases, to identify the parent cluster, i.e., the stellar group where the runaway originated (e.g., Blaauw 1993).

Two mechanisms for the production of runaway stars remain viable: the *binary-supernova scenario* (Zwicky 1957; Blaauw 1961) and the *dynamical ejection scenario* (Poveda, Ruiz, & Allen 1967; Gies & Bolton 1986). In the former, the runaway receives its velocity after a supernova explosion in a massive close binary; after the explosion the binary (sometimes) dissociates and the secondary starts to move through space with a velocity comparable to its preexplosion orbital velocity. Examples of systems where the binary remains bound include the high-mass X-ray binaries, with typical velocities of ~ 50 km s $^{-1}$ (Kaper et al. 1997; van den Heuvel et al. 2000). In the latter scenario, the runaway gains its velocity through a dynamical interaction with one or more other stars. The most efficient encounter is that between two hard binaries, which, in most cases, results in the ejection of two runaway stars and one eccentric binary (Hoffer 1983; Mikkola 1983).

Which of the two mechanisms dominates the creation of runaway stars has been debated vigorously in the past. The modest accuracy and incompleteness of previous data sets did not allow distinguishing convincingly between the two mechanisms; both scenarios were consistent with the statistical properties of the ensemble of runaway stars. The availability of *Hipparcos* milliarcsecond astrometry for the nearby stars (ESA 1997) and pulsar astrometry provided by VLBI and timing measurements stimulated us to revisit this issue, as it allows calculation of the past orbits of these objects with sufficient

accuracy to establish their parent group and the mechanism that formed them. A past encounter between a single runaway star and a pulsar would provide compelling evidence for the binary-supernova scenario, while an encounter of two (or more) runaway stars would strongly suggest the dynamical ejection scenario. In the course of this work, we could identify the specific formation scenario for three nearby runaways (the pair AE Aurigae, μ Columbae and ζ Ophiuchi) with near certainty.

In this Letter, we summarize the results for these objects, as together they demonstrate that both mechanisms for the creation of runaway stars operate in nature. Details of the orbit integrations, the Galactic potential used, and the simulations performed to validate the results, as well as a discussion of the other nearby runaway stars and pulsars with accurate astrometry, are reported in Hoogerwerf, de Bruijne, & de Zeeuw (2000, hereafter HBZ).

2. A STELLAR ENCOUNTER IN ORION

The Orion association (Ori OB1) has three known runaway stars: AE Aur, μ Col, and 53 Ari (Blaauw 1961). The first two of these form a pair; they have almost similar spectral types (O9.5 V and O9.5 V/B0) and move in opposite directions at 100 km s $^{-1}$ each, leaving Ori OB1 about 2.5 Myr ago. These similarities led Blaauw & Morgan (1954) to suggest that the two stars were formed in the same event. Gies & Bolton (1986) proposed that AE Aur, μ Col, and the massive eccentric binary ι Orionis (O9 III + B1 III) are the result of a binary-binary encounter that ejected the two runaways. Both stars have normal rotational velocities (25 and 111 km s $^{-1}$ for AE Aur and μ Col, respectively), and AE Aur has a normal He abundance. The He abundance of μ Col is unknown. Thus, neither runaway shows signs of previous mass transfer in a close binary system, and this most likely excludes the binary-supernova scenario as the origin of the two runaways (Blaauw 1993). Dynamical ejection is by far the favorite scenario for the origin of the high velocities of AE Aur and μ Col.

We supplemented the *Hipparcos* astrometry with the best available radial velocities in order to retrace the orbits of AE Aur, μ Col, and ι Ori. We performed 2.5×10^6 orbit in-

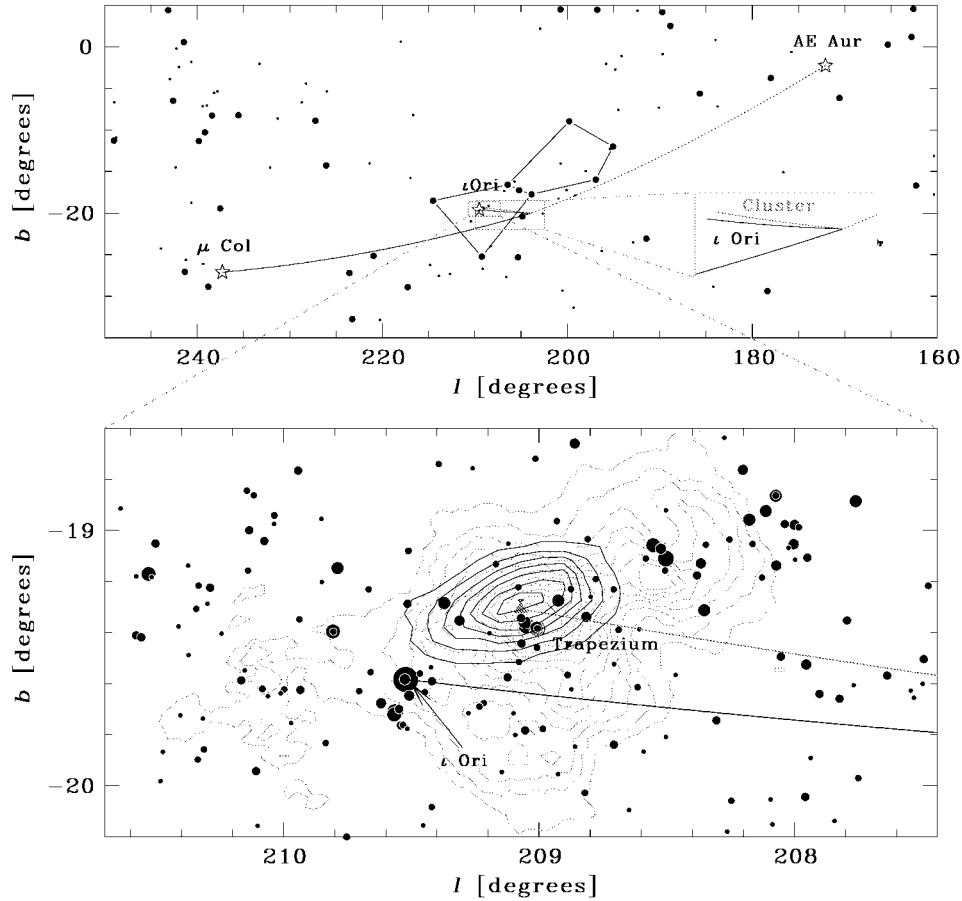


FIG. 1.—*Top*: Past orbits on the sky of the runaways AE Aur (*dotted line*) and μ Col (*solid line*) and of the binary ι Ori. The star symbols depict the present position of the three stars. The orbit of the parent cluster is denoted by the solid gray line. The filled circles denote all stars in the *Hipparcos* Catalogue brighter than $V = 3.5$ mag (*large*) and with $3.5 \text{ mag} \leq V \leq 5$ mag (*small*; only the O and B stars) (cf. Fig. 1 in Blaauw & Morgan 1954). The Orion constellation is indicated for reference. *Bottom*: The black contours denote the normalized probability distribution of the predicted position of the parent cluster based on 10,000 orbit integrations and are spaced linearly. The filled circles indicate all stars in the Tycho Catalogue (ESA 1997) in the field. The size of the symbols scales with magnitude. The black and dark gray lines are the past orbits of ι Ori and the Trapezium, respectively (see top panel). The gray contours display the IRAS 100 μm flux map, spaced logarithmically, and mainly outline the Orion Nebula.

tegrations to sample the errors in the positions and velocities of the objects. These integrations use the observed positions and velocities as starting points for a numerical integration of the equations of motion in a Galactic potential that reproduces the measured values of Oort's constants and circular rotation velocity (see HBZ). The integrations show that ~ 2.5 Myr ago the three stars were very close together: the distribution of minimum separations obtained from the orbit integrations is consistent—within the measurement errors—with the stars being located in exactly the same position in space at the same time, 2.5 ± 0.2 Myr ago. We therefore conclude that the two runaway stars and the binary ι Ori must once have been part

of the same cluster and were all ejected following a dynamical interaction.

A natural question to ask is which cluster hosted the four stars before their encounter? Assuming that the center-of-mass motion of the four stars was similar to that of the parent cluster and using conservation of linear momentum provides the position and velocity of the parent cluster ~ 2.5 Myr ago. We integrated its orbit forward in time to the present (Fig. 1). The resulting properties of the parent cluster, specifically, its distance (D), position on the sky, proper motion (μ), and radial velocity (v_{rad}), agree very well with that of the Trapezium cluster (see Table 1 and Fig. 1).

Several other properties of the Trapezium cluster strengthen the conclusion that this is the most likely candidate for being the parent of AE Aur, μ Col, and ι Ori. First, the Trapezium is a very young cluster, ~ 2 Myr (Palla & Stahler 1999); its density ($>20,000$ stars pc^{-3} in the center) is still high enough for stellar encounters to occur. At the same time, the Trapezium is old enough to have existed when the runaways left the cluster ~ 2.5 Myr ago. Second, the Trapezium shows a strong mass segregation (Zinnecker, McCaughrean, & Wilking 1993; Hillenbrand & Hartmann 1998); this concentration of massive stars increases the probability for dynamical encounters between

TABLE 1

PREDICTED PROPERTIES OF THE PARENT CLUSTER OF AE AUR AND μ COL AND OBSERVED PROPERTIES OF THE TRAPEZIUM

Property	Parent Cluster	Trapezium
D (pc)	425–450	450–500
(α, δ) (deg)	(83.9, -5.2)	(83.8, -5.4)
$(\mu_{\alpha*}, \mu_{\delta})$ (mas yr^{-1})	(1.7, -0.2)	(2.7, -0.9)
(l, b) (deg)	(208.9, -19.2)	(209.0, -19.4)
(μ_{l*}, μ_b) (mas yr^{-1})	(0.9, 1.4)	(2.0, 2.0)
v_{rad} (km s^{-1})	27.6	24

stars. Third, the binary fraction in the Trapezium is high, 60%–100% (Prosser et al. 1994; Weigelt et al. 1999). This also increases the chance of dynamical encounters since binary-binary collisions are the most efficient.

3. A SUPERNOVA IN UPPER SCORPIUS

Blaauw (1952) identified the O9.5V star ζ Oph as a runaway originating in the Sco OB2 association. The star could either have left the Upper Scorpius subgroup ~ 1 Myr ago or the Upper Centaurus Lupus subgroup ~ 3 Myr ago. The intrinsic properties of ζ Oph (observed rotational velocity $v_{\text{rot}} \sin i = 350 \text{ km s}^{-1}$ and He abundance $Y = 0.40$) indicate that the star previously experienced mass transfer in a close binary system. As ζ Oph is single at present (Gies & Bolton 1986), the binary must have dissociated sometime in the past. This led to the suggestion that ζ Oph is a runaway created in a binary supernova explosion. Finding a compact object formed in the same event would prove that this assumption is correct.

Radio pulsars are the only neutron stars for which reliable and accurate proper-motion measurements are available. Of all pulsars in the Taylor, Manchester, & Lyne (1993) catalog,¹ only seven are within 1 kpc and have proper motions with better than 10% accuracy. Six of the seven cannot be related to ζ Oph, based on their (three-dimensional) position and velocity relative to ζ Oph, their position and velocity relative to the Galactic plane, or their characteristic age $P/(2\dot{P})$ (see HBZ for details). The pulsar that remains is PSR J1932+1059 (also known as B1929+10); it has a characteristic age of ~ 3 Myr, and it traversed the Upper Scorpius region about 1 Myr ago if its (unknown) radial velocity $v_{\text{rad}} = 200 \pm 50 \text{ km s}^{-1}$ (see Fig. 2).

The pulsar currently moves away from the Galactic plane with a z -velocity of $\sim 40 \text{ km s}^{-1}$ and is located at a Galactic latitude of $b \sim -4^\circ$. Assuming that most neutron stars are created in or near the Galactic disk, PSR J1932+1059 must have formed either recently or some 50 Myr ago, when its past orbit again crossed the Galactic plane (e.g., Blaauw & Ramachandran 1998). Taking into account its characteristic age, it is natural to assume that the pulsar was formed recently. The only site of active or recent star formation along the pulsar's path is Upper Scorpius, and this young stellar group therefore is the only likely birth site for PSR J1932+1059.

We integrated the orbits of ζ Oph, the pulsar, and Upper Scorpius back in time in a standard Galactic potential. We performed 3×10^6 such integrations to sample the error distributions in position and velocity. The main uncertainties are the errors in the parallax of ζ Oph ($7.1 \pm 0.7 \text{ mas}$) and the pulsar ($5 \pm 1.5 \text{ mas}$; Campbell 1995) and the remaining range in v_{rad} . The distribution of the minimum distance between ζ Oph and the pulsar is consistent with zero distance within the measurement errors, i.e., with both objects being in the same location, $1.0 \pm 0.1 \text{ Myr}$ ago in Upper Scorpius (Fig. 2). This is strong evidence for the binary supernova scenario.

The kinematics of the expanding H I shell that surrounds Upper Scorpius requires a supernova explosion 1–2 Myr ago, and the present-day mass function of the subgroup suggests that originally one more massive star or binary ($\sim 40 M_\odot$) must have been present (de Geus 1992). The simplest interpretation is that this was a close binary containing ζ Oph and the progenitor of PSR J1932+1059.

Based on models of binary evolution, van Rensbergen, Vanbeveren, & de Loorevan (1996) suggested that ζ Oph originated

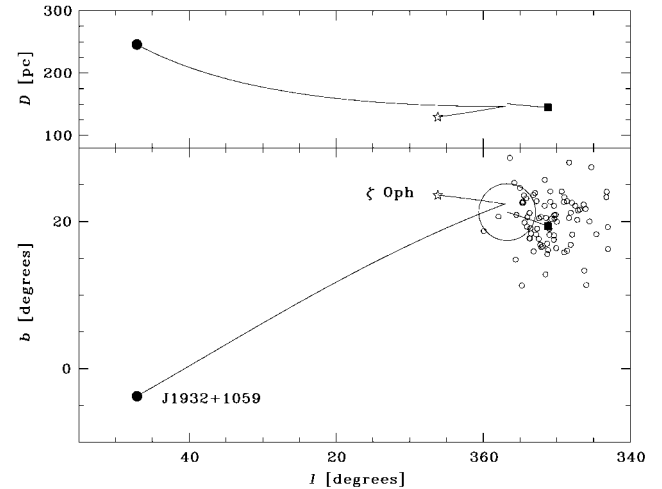


FIG. 2.—Orbits of ζ Oph, PSR J1932+1059, and Upper Scorpius. The present positions are denoted by a star for the runaway, a filled circle for the pulsar, and a filled square for the center of the association. *Top*: The distance vs. Galactic longitude of the stars. *Bottom*: The orbits projected on the sky in Galactic coordinates. The small open circles in the bottom panel denote the present-day positions of the O-, B-, and A-type members of Upper Scorpius (de Zeeuw et al. 1999). The large circle denotes the position of the association at the time of the supernova explosion (10 pc radius). This figure assumes a set of space motions consistent with all observables.

in a binary-supernova event in Upper Centaurus Lupus about 3 Myr ago. In this case ζ Oph and PSR J1932+1059 are not related because the pulsar never came near this subgroup. Given the small probability of finding a runaway and a pulsar with orbits that intersect, and with both objects at the point of intersection at the same time, we consider it more likely that ζ Oph and PSR J1932+1059 were once part of the same close binary in Upper Scorpius.

The value of $P/(2\dot{P})$ is an uncertain age indicator, and ~ 3 Myr for PSR J1932+1059 is consistent with the kinematical age of 1 Myr derived here. The implied period at birth is 0.18 s; the current period is 0.22 s.

Pulsars are expected to receive a kick velocity v_{kick} at birth (e.g., Lai 2000). Observations of the ensemble of pulsars suggest that the magnitude of v_{kick} is a few hundred kilometers per second (Hartman 1997; Hansen & Phinney 1997). Assuming that ζ Oph and PSR J1932+1059 originated in the same binary allows an individual determination of v_{kick} . Based on the magnitude of the space velocities and the angle between the orbits of ζ Oph and the pulsar, we obtain $|v_{\text{kick}}| = 350 \pm 50 \text{ km s}^{-1}$. New VLBI observations of the proper motion and parallax of PSR J1932+1059 are being obtained by R. M. Campbell (2000, private communication) and will make it possible to improve this estimate further.

4. CONCLUSIONS

The cases described in the previous two sections provide the first *specific* evidence that both the binary-supernova scenario and the dynamical ejection scenario can produce single runaway stars. This result is based on a detailed analysis of the orbits of three runaway stars, in contrast to earlier investigations that mainly focused on the *statistical* properties of a set of runaway stars. Our systematic study of the nearby runaway stars and pulsars (HBZ) provides the parent group for 18 additional runaway stars and two more pulsars. The new runaways include another pair of stars traveling at high speed in opposite

¹ Updated on <http://pulsar.princeton.edu>.

directions, originating in the region of the λ Ori cluster. We find that about two-thirds of these runaways were produced in a binary supernova event, while the remaining one-third acquired their high velocity in a dynamical ejection.

Determination of the fraction of the runaway stars created by either mechanism will put strong constraints on cluster formation theories and on stellar evolution theories. Numerical simulations such as those performed by Portegies Zwart (2000) show that runaway statistics can put limits on, for example, the number of primordial binaries. However, the current samples of runaway stars and pulsars with accurate astrometry are severely incomplete. The *Hipparcos* Catalogue is complete only for $V < 7.3$ –9 mag (depending on latitude), and less than one-third of the O and B stars in it have a measured radial velocity. Because of beamed radio emission, we cannot observe all pulsars, and not all of those that do radiate in our direction have been found in the solar neighborhood; of these, only a few have an accurately measured proper motion. Even though the HBZ study is somewhat biased toward finding binary-

supernova runaways, the available data supports the tentative conclusion that both mechanisms contribute about equally to the production of runaway stars (see HBZ).

The approach followed here promises many new results once the next generation of astrometric satellites, e.g., the *Full-Sky Astrometric Mapping Explorer* and in particular *GAIA*, are launched and VLBI techniques are developed fully. These will improve the accuracy of the astrometry for stars and pulsars into the microarcsecond regime. With a fainter limiting magnitude, many more runaways will have well-determined positions and velocities. It will then be possible to identify the parent clusters of these objects and to learn much about the ages and kick velocities of individual pulsars.

It is a pleasure to thank Adriaan Blaauw, Bob Campbell, Nicolas Cretton, Ed van den Heuvel, Rob den Hollander, Michael Perryman, and Simon Portegies Zwart for useful comments and suggestions.

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