Binary Interaction Dominates the Evolution of Massive Stars

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Supplementary Materials
www.sciencemag.org/cgi/content/full/337/6093/437/DC1
Materials and Methods
Supplementary Text
Figs. S1 to S11
Table S1
References (*48–60*)
Movie S1
Databases S1 to S9

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Binary Interaction Dominates the Evolution of Massive Stars

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The presence of a nearby companion alters the evolution of massive stars in binary systems, leading to phenomena such as stellar mergers, x-ray binaries, and gamma-ray bursts. Unambiguous constraints on the fraction of massive stars affected by binary interaction were lacking. We simultaneously measured all relevant binary characteristics in a sample of Galactic massive O stars and quantified the frequency and nature of binary interactions. More than 70% of all massive stars will exchange mass with a companion, leading to a binary merger in one-third of the cases. These numbers greatly exceed previous estimates and imply that binary interaction dominates the evolution of massive stars, with implications for populations of massive stars and their supernovae.

With masses larger than 15 times that of our Sun (*1*), stars of spectral type O are rare (*2*) and short-lived (*3*). Nevertheless, through their large luminosities, strong stellar winds, and powerful explosions, massive stars heat and enrich surrounding gas clouds in which new generations of stars form (*4*) and drive the chemical evolution of galaxies (*5*). Massive stars end their lives in luminous explosions, as core-collapse supernovae (CCSN) or gamma-ray bursts (GRBs), that can be observed throughout most of the universe.

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In a binary system, the evolutionary path of a massive star is drastically altered by the presence of a nearby companion (*6–8*). Because stars expand as they evolve, those in pairs with orbital periods up to ~1500 days exchange mass (*6*). The more massive star can be stripped of its entire envelope and, thus, loses much of its original mass. The companion star gains mass and angular momentum, which trigger mixing processes in the stellar interior and modify its evolutionary path (*3*). In very close binaries, the two stars may even merge. The nature of the binary interaction is largely determined by the initial orbital period and mass ratio. The relative roles of interaction scenarios and the overall importance of binary- versus single-star evolution so far remain uncertain because of the paucity of direct measurements of the intrinsic distributions of orbital parameters (*9–14*).

In this work, we homogeneously analyze the O star population of six nearby Galactic open stellar clusters and simultaneously measure all the relevant intrinsic multiplicity properties (*15*). Our observational method, spectroscopy, is sensitive to orbital periods as long as 10 years (*13*), corresponding to the relevant period range for binary interaction (*6*). In a spectroscopic binary, the periodic Doppler shift of spectral lines allows the determination of the radial velocity and, hence, of the orbital motion of one ("single-lined" spectroscopic binary) or both ("double-lined" spectroscopic binary) stars. Given sufficient orbital-phase coverage, the orbital period (P), the eccentricity (e), and, for double-lined spectroscopic binaries, the mass-ratio (q) follow from Kepler's laws.

Our sample contains 71 single and multiple O-type objects (see supplementary text A). With 40 identified spectroscopic binaries, the observed binary fraction in our sample is $f_{\rm obs}$ = 40/71 = 0.56. We combined observations obtained with the Ultraviolet and Visible Echelle Spectrograph at the Very Large Telescope for long-period systems with results from detailed studies of detected systems in the individual clusters (*16–21*). In total, 85 and 78% of our binary systems have, respectively, constrained orbital periods and mass ratios. This allowed us to build statistically significant observed period and mass-ratio distributions for massive stars (Fig. 1), which are representative of the parameter distributions of the Galactic O star population (*13*).

The precise fraction of interacting O stars and the relative importance of the different interaction scenarios are determined by the distributions of the orbital parameters. The observed distributions result from the intrinsic distributions and the observational biases (see supplementary text B). To uncover the intrinsic distributions, we simulate observational biases with the use of a Monte Carlo approach that incorporates the observational time series of each object in our sample. We adopt power laws for the probability density functions of orbital periods (in $\log_{10}$ space), mass ratios, and eccentricities with exponents π, κ, and η, respectively (fig. S3 and table S3). These power-law exponents and the intrinsic binary fraction $f_{\rm bin}$ were simultaneously determined by a comparison of simulated populations of stars with our sample allowing for the observational biases. We determined the accuracy of our method by applying it to synthetic data.

Compared with earlier attempts to measure intrinsic orbital properties (*9–14*): (i) The average number of epochs per object in our sample is larger by up to a factor of 5, making binary detection more complete. (ii) More than

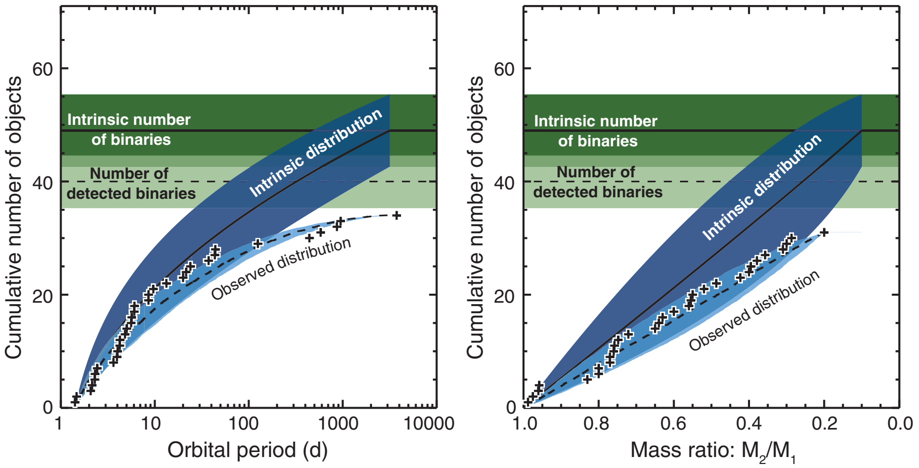

Fig. 1. Cumulative number distributions of logarithmic orbital periods (**left**) and mass ratios (**right**) for our sample of 71 O-type objects, of which 40 are identified binaries. The horizontal solid lines and the associated dark green areas indicate the most probable intrinsic number of binaries (49 in total) and its 1σ uncertainty, corresponding to an intrinsic binary fraction f_{bin} = 0.69 ± 0.09. The horizontal dashed lines indicate the most probable simulated number of detected binaries (40 ± 4), which agrees very well with the actual observed number of binaries (40 in total). Crosses denote the observed cumulative distributions for systems with known periods (34 in total) and mass ratios (31 in total). The lower dashed lines indicate the best simulated observational distributions and their 1σ uncertainties, corresponding to intrinsic distributions with power-law exponents π = −0.55 ± 0.22 and κ = −0.10 ± 0.58, respectively. The lower solid lines and associated dark blue areas indicate the most probable intrinsic number distributions and their errors. The latter were obtained from a combination of the uncertainties on the intrinsic binary fraction and on the power-law exponents of the respective probability density functions. d, days.

three-quarters of our binaries have measured orbital properties, which allowed us to directly model the orbital parameter distributions. (iii) The orbital properties cover the full range of periods and mass ratios relevant for binary interaction. Thus, we are better equipped to draw direct conclusions about the relative importance of various binary interaction scenarios.

We find an intrinsic binary fraction of f_{bin} = 0.69 ± 0.09, a strong preference for close pairs (π = −0.55 ± 0.2), and a uniform distribution of the mass ratio (κ = −0.1 ± 0.6) for binaries with periods up to about 9 years. Comparison of the intrinsic, simulated, and observed cumulative distributions of the orbital parameters shows that observational biases are mostly restricted to the longest periods and the most extreme mass ratios (Fig. 1).

Compared with previous works, we find no preference for equal-mass binaries (*22*). We obtain a steeper period distribution and a larger fraction of short period systems than previously thought (*9*–*14*, *23*), resulting in a much larger fraction of systems that are affected by binary evolution.

Because star-cluster dynamics and stellar evolution could have affected the multiplicity properties of only very few of the young O stars in our sample (see supplementary text A.2), our derived distributions are a good representation of the binary properties at birth. Thus, it is safe

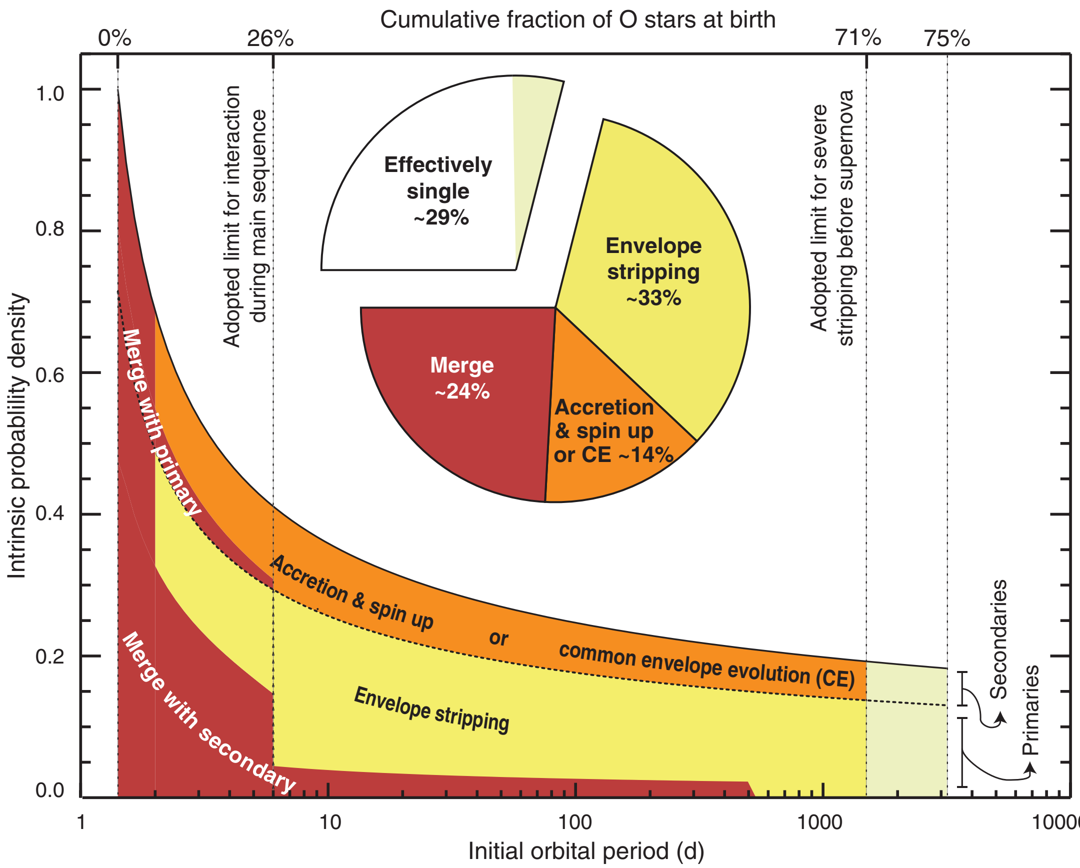

Fig. 2. Schematic representation of the relative importance of different binary interaction processes given our best-fit binary fraction and intrinsic distribution functions. All percentages are expressed in terms of the fraction of all stars born as O-type stars, including the single O stars and the O stars in binaries, either as the initially more massive component (the primary) or as the less massive one (the secondary). The solid curve gives the best-fit intrinsic distribution of orbital periods (corresponding to π = −0.55), which we adopted as the initial distribution. For the purpose of comparison, we normalized the ordinate value to unity at the minimum period that we considered. The dotted curve separates the contributions from O-type primary and secondary stars. The colored areas indicate the fractions of systems that are expected to merge (red), experience stripping (yellow), or accretion/common envelope evolution (orange). Assumptions and uncertainties are discussed in the text and in supplementary text C. The pie chart compares the fraction of stars born as O stars that are effectively single [i.e., single (white) or in wide binaries with little or no interaction effects (light green)—29% combined] with those that experience significant binary interaction (71% combined).

to conclude that the most common end product of massive-star formation is a rather close binary. This statement challenges current star formation theories (*24*). However, according to recent simulations (*25*, *26*), accretion disk fragmentation, through gravitational instabilities, seems to naturally result in the formation of binary systems containing two massive stars with similar but not equal masses (i.e., within a factor of a few). Though the companions are initially formed in a wide orbit, dynamical interactions with the remnant accretion disk may substantially harden the system, thus providing a better agreement with the observations.

Intrinsic binary properties are key initial conditions for massive-star evolution; that is, evolutionary paths and final fates. Integration of our intrinsic distribution functions (Fig. 2 and supplementary text C) implies that 71% of all stars born as O-type interact with a companion, over half of which do so before leaving the main sequence. Such binary interactions drastically alter the evolution and final fate of the stars and appear, by far, the most frequent evolutionary channel for massive stars. Based on calculations of binary evolution in short-period systems (*6*, *27*–*29*), we also find that 20 to 30% of all O stars will merge with their companions and that 40 to 50% will either be stripped of their envelope or will accrete substantial mass (see supplementary text C). In summary, we find that almost three-quarters of all massive stars are strongly affected by binary interaction before they explode as supernovae.

The interaction and merger rates that we computed are, respectively, two and three times larger than previous estimates (*6*, *11*, *23*). This results in a corresponding increase in the number of progenitors of key astrophysical objects, such as close double compact objects, hydrogen-deficient CCSN, and GRBs, that are thought to be produced by binary interaction.

We predict that 33% of O stars are stripped of their envelope before they explode as hydrogen-deficient CCSN (types Ib, Ic, and IIb). This fraction is close to the observed fraction of hydrogen-poor supernovae; that is, 37% of all CCSN (*30*). Extrapolation of our findings from O stars to the 8– to 15–solar mass range to include all CCSN progenitors implies that hydrogen-poor CCSN predominantly result from mass transfer in close binaries. This rate is large enough to explain the discrepancy between the large observational fraction of type Ib/c supernovae and the dearth of single stars stripped by stellar winds. Our results also imply that more than half of the progenitors of hydrogen-rich (type II) supernovae are merged stars or binary mass gainers, which might explain some of the diversity of this supernova class.

Our results further indicate that a large fraction of massive main-sequence stars (~40%) is expected to be spun-up either by accretion or coalescence. In lower-metallicity galaxies, these stars should remain rapidly rotating and, hence, constitute a major channel for the production of long-duration GRBs (*31*), which are thought to accompany the death of massive stars in case their iron cores collapse to critically rotating neutron stars or black holes (*32*, *33*).

In sum, we show that only a minority of massive stars evolve undisturbed toward their supernova explosions. Hence, the effects of binarity must be considered to further our understanding of the formation and evolution of massive stars and to help us interpret the integrated properties of distant star-forming galaxies (*34*, *35*).

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Supplementary Materials

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Supplementary Text
Figs. S1 to S4
Tables S1 to S4
References (*36*–*62*)

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Excitation of Orbital Angular Momentum Resonances in Helically Twisted Photonic Crystal Fiber

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Spiral twisting offers additional opportunities for controlling the loss, dispersion, and polarization state of light in optical fibers with noncircular guiding cores. Here, we report an effect that appears in continuously twisted photonic crystal fiber. Guided by the helical lattice of hollow channels, cladding light is forced to follow a spiral path. This diverts a fraction of the axial momentum flow into the azimuthal direction, leading to the formation of discrete orbital angular momentum states at wavelengths that scale linearly with the twist rate. Core-guided light phase-matches topologically to these leaky states, causing a series of dips in the transmitted spectrum. Twisted photonic crystal fiber has potential applications in, for example, band-rejection filters and dispersion control.

The effect of twisting on the propagation of light in different kinds of optical fibers has been explored for polarization control (*1*–*3*), long-period grating couplers (*4*–*7*), and elimination of higher-order modes from fiber lasers (*8*). We study twisted solid-core