PERSPECTIVES: ASTRONOMY

White Dwarf Mergers and the Rebirth of Luminous Stars

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Stars are born in cold clouds of interstellar dust and gas. They first generate energy by thermonuclear fusion ("burning") of hydrogen (H) into helium (He) and, after several stages of thermonuclear evolution in their interior, end their life as compact remnants. In the absence of nuclear energy, they cool and fade to invisibility. More than 99% of the stars in our Galaxy finally become white dwarfs; the others end as neutron stars or occasionally as black hole remnants of stellar explosions.

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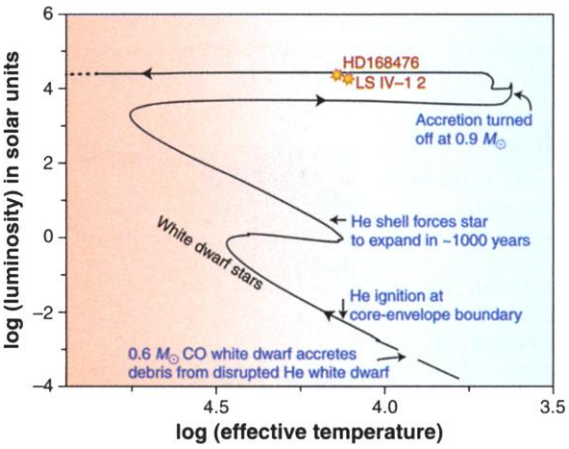
Theory indicates that white dwarf remnants are about as small as Earth and may consist either of He or carbon and oxygen (C/O). C/O white dwarfs emerge from stars like our Sun, whereas He white dwarfs are expected to originate from stars with a mass less than half that of the Sun. The latter burn H for much longer than the present age of the universe. Because low-mass stars outnumber more massive ones, He white dwarfs should eventually take over as the Galaxy ages. But low-mass stars are not yet burnt out and we do not expect He white dwarfs to exist in our present-day Galaxy, where all white dwarfs should be of the C/O type.

Observations have shown, however, that a small fraction of white dwarfs are of the He type (*1*). We therefore have to consider additional formation scenarios. The most promising candidates are close binary stars. In this case, the He white dwarf results from an interaction of its progenitor with a close companion star. After exhausting its H fuel, the progenitor expands to giant dimensions and transfers its envelope to the companion before the He core has grown to the critical mass of half a solar mass: A He white dwarf is born.

Several He white dwarfs have faint companions that are white dwarfs themselves (*1*), either of the He or of the C/O type. According to model estimates, there should be as many as 250 million double white dwarf systems among the hundred billion stars of our Galaxy (*2*). Such double white dwarf systems cannot exist forever. Einstein's theory of general relativity predicts the emission of gravitational waves (*3*), leading to a loss of angular momentum and decay of the binary orbit. Finally, the components will coalesce. The time scale of orbital shrinkage depends strongly on the orbital period of the system; long-period systems will take 10^{18} to 10^{24} years or more to coalesce. But if the separation of the two white dwarfs is sufficiently small, they can coalesce in less time than the age of the Galaxy.

Well before the first double white dwarf system was discovered in 1988 (*4*), it was predicted (*5*) that such double white dwarf mergers can occasionally result in supernova explosions (when two massive C/O white dwarfs merge), but should mostly produce peculiar luminous stars (when a C/O and a He white dwarf or two He white dwarfs coalesce). In a recent paper in *Monthly Notes of the Royal Astronomical Society*, Saio and Jeffery (*6*) follow up on this idea by calculating the evolution of objects formed by merging a binary consisting of a C/O and a He white dwarf.



When white dwarfs merge. Evolution of a C/O white dwarf that accretes the debris of its disrupted He white dwarf companion in the surface temperature–luminosity diagram. The original white dwarfs had 0.6 and 0.3 solar masses ($M_\odot$), respectively. The position of the two extreme He stars are marked in red. Finally, the system will evolve into a single white dwarf of 0.9 $M_\odot$. See also the animation at www.arm.ac.uk/~csj/movies/merger.html.

When the distance between the stars orbiting each other shrinks to a few Earth diameters, mass transfer starts as the more massive C/O white dwarf disrupts the He white dwarf and accretes its debris (see the figure) (*6*). A He-rich envelope forms around the C/O white dwarf and He is ignited at the core-envelope boundary. The star expands to giant dimensions of hundreds of solar radii. Its luminosity increases to about 10,000 times the luminosity of the Sun.

During the merger, some C and O is mixed up into the He envelope from the underlying C/O white dwarf (*6*). Traces of H that existed on the surface of the stars are burnt into He and nitrogen (N). We therefore expect the observable surface of the reborn giant star to consist mainly of He, with some C, N, and O. This surface composition is very different from that of normal stars like the Sun, which are dominated by H, followed by He and O, which are, respectively, 10 and 1000 times less abundant than H.

Do stars with such a peculiar surface composition exist in our Galaxy? A few dozen stars that could fit the model prediction have been discovered. They are named after the prototype R CrB in the constellation Corona Borealis, one of the first stars discovered to be variable more than 200 years ago. Together with their rare hotter sisters, the extreme He stars, they form a class of peculiar giant stars (*7*). The extreme He stars contract so rapidly that it has been possible to measure a slight increase in surface temperature in less than 20 years (*8*).

To validate the merger scenario for the formation of such stars, the following tests have been made. First, the stars should no longer have any companions. It is difficult to exclude binarism, but no indication for binarity among extreme He stars has been found. Second, the observed luminosities and abundances of He, C, N, and O have to be consistent with model predictions. Saio and Jeffery demonstrate a close match to the observed luminosities and abundances when a few model parameters are properly adjusted. Third, the evolutionary lifetimes predicted by the model calculations have to match the number of these peculiar giants in the Galaxy. The model calculations predict slightly more of the hot extreme He stars than are known in the Galaxy but too few of the cooler R CrB stars.

These tests validate the white dwarf merger scenario for the formation of R CrB and extreme He stars. The question remains, however, whether it is the only formation channel for R CrB stars. The third test should answer this question, but model predictions for the number of R CrB stars in the Galaxy formed by mergers are rather

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uncertain (by a factor of 3 or worse). Within this large margin the observed number of R CrB stars is consistent with the merger scenario as the only formation channel. Crucial model parameters will soon be known much better from a large survey of double white dwarfs with the Very Large Telescope of the European Southern Observatory (*9*).

The driving agent that leads to the merging of the white dwarfs is the emission of gravitational waves. Such waves have not yet been measured. First detections may be possible soon with sensitive ground-based laser-interferometric detectors, due to become operational by the end of the year (*10*). But the low-frequency gravitational waves emitted by double white dwarfs will be buried in the background noise. Their detection will have to await the operation of the space-born LISA observatory, planned for launch in the next decade.

In the far and dark future of the universe, when all stars have burnt their nuclear fuel and turned into cold, compact remnants, lots of double white dwarfs should exist. He white dwarfs should then be more numerous. Their merger will lead to the rebirth of He-burning stars (*11*) known as sdB stars (*12*), which are less luminous (about 30 times the solar luminosity) but live longer (100 million years) than R CrB stars. The dark universe will then be lit from time to time by R CrB and sdB stars for a while, until all of them have contracted to the white dwarf graveyard.

References and Notes

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12. Unlike the R CrB stars, the white merger process is probably only a minor formation channel for the sdB stars observed in the present-day Galaxy.

PERSPECTIVES: SIGNAL TRANSDUCTION

MAP Kinase Signaling Specificity

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Where would cells be without mitogen activated protein kinases (MAPKs)? These molecules are components of signaling pathways that relay, amplify, and integrate signals from a variety of extracellular stimuli, thereby controlling the genomic and physiological response of a cell to its environment. In mammals, MAPKs guide cellular maturation and can induce inflammation and apoptosis. The MAPK family includes extracellular signal–regulated kinases (ERKs), which are activated by mitogens, and c-Jun NH$_2$-terminal kinases (JNKs) and p38 MAPKs that are primarily activated by cytokines and in response to cellular stress. With all of these related kinases in the same place, how does the cell keep the pathways distinct from one another? It turns out that many mechanisms exist to prevent cross talk between pathways, thereby ensuring that the cell responds correctly to each environmental challenge.

One way that MAPKs maintain specificity is to physically bind to other proteins in their information cascade through highly specific docking sites (*1*, *2*). Many MAPKs contain the common docking (CD) site and the Glu-Asp (ED) site; MAPK interacting proteins have D domains. The structural basis for these precise interactions remained elusive until Chang and colleagues resolved the crystal structure of p38 MAPK bound to the docking domains of a p38 substrate and a p38-activating enzyme (*3*).

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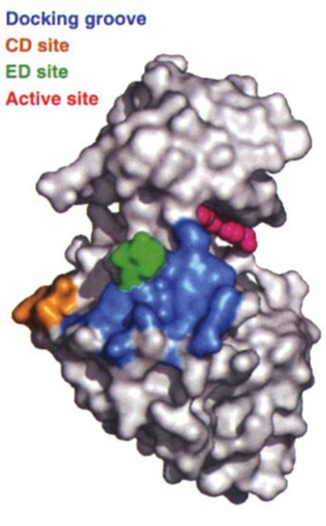
In their report in *Molecular Cell*, Chang and colleagues used isolated D domains from transcription factor MEF2A (a p38 substrate), and from the p38-activating enzyme MKK3b. Both of these docking domains, like other D domains, contain basic residues and a hydrophobic ØA-X-ØB motif (where ØA and ØB are hydrophobic residues Leu, Ile, or Val). The D domain—first identified in c-Jun (which binds to JNK), MEF2 (which binds to p38), and Elk-1 (which binds to ERK and JNK) (*4–6*)—contains two to six residues that separate a hydrophobic ØA-X-ØB motif from a cluster of at least two basic residues (Lys, Arg). Both the basic and the hydrophobic residues of the D domain are vital to the recognition and binding of specific MAPK isoforms (*1*, *2*). Many different types of MAPK-interacting proteins, including activating enzymes (MAPKK), scaffold proteins, phosphatases, and substrates, have similar D domains, while some interacting proteins contain the related Phe-X-Phe-Pro (FXFP) MAPK binding domain (*1*, *2*).

Chang and colleagues uncovered many details in the crystal structure of p38 MAPK bound to the docking domains of MEF2A and MKK3b. For example, both domains bind to the same site, a groove present between α helices αd and αe and the reverse turn between β7 and β8 in the COOH-terminal region of the kinase (see the first figure). Residues Ile^{116} and Gln^{120} in this docking groove are essential for the recognition of the ØA-X-ØB motif and thus for the docking interaction. This docking groove is separate from the kinase active site and from the CD site previously implicated in MAPK docking interactions (*7*). Docking grooves similar to the one identified by Chang and colleagues appear in other MAPKs, so the groove is not unique to p38 (*3*). Nevertheless, many of the residues in p38 that contact the D domain differ between MAPK isoforms, which suggests that the structure of the docking groove in individual MAPK isoforms determines MAPK selectivity.



The binding site. Molecular surface representation of p38α MAPK, showing the docking groove (blue) that binds the D domains of the substrate MEF2A and the activator MKK3b. The CD site (orange) and ED site (green) that were identified in biochemical studies. The active site of p38 MAP kinase is bound to the inhibitor SB203580 (red).

In previous biochemical studies, researchers identified the CD site as a common docking site that mediates MAPK interactions with other proteins and is distinct from the catalytic active site of MAPK (*8*). Specifically, the acidic residues in the CD site were proposed to interact with the basic residues in the D domain of the binding partner. Chang and colleagues did not observe this interaction in the p38 MAPK crystal structures. The failure to confirm this proposed structure may reflect differences in the interactions of MAPK with various substrates. Alter-