A hypothesis or theory is clear, decisive, and positive, but it is believed by no one but the person who created it. Experimental findings, on the other hand, are messy, inexact things, which are believed by everyone except the person who did that work.

> Harlow Shapley Through Rugged Ways to the Stars

Smashing White Dwarfs: Book One of the Supernovae Trilogy

Frank Timmes









Starlib

THE ASTROPHYSICAL JOURNAL







White dwarf supernova play a key role in astronomy:

Distance indicators Element factories Cosmic-ray accelerators Kinetic energy sources Binary star terminus

Identification of what is exploding is unknown - this is the outstanding mystery in the field.



Tycho Supernova Remnant:

Age: - Nov 1572 Distance: ~ 8500 ly Diameter: ~ 18 ly (8 arc min) Expansion: ~ 0.0015 ly/yr

Blue - high energy electrons Green & Yellow - iron and silicon Red - dust Several observational characteristics help in the hunt for the progenitors of the explosions:

 About 90% of all white dwarf supernova form a homogeneous class in terms of their spectra and light curves. White dwarf supernovae are defined by their spectra: no hydrogen lines and a strong silicon absorption feature.





Normalized Flux (F_{λ}) + Const.

Near maximum light, spectra are characterized by O-Ca at high velocity (~20k km/s).

Late nebular phase spectra are dominated by iron lines.





Several observational characteristics help in the hunt for the progenitors of the explosions:

 About 90% of all white dwarf supernova form a homogeneous class in terms of their spectra and light curves.

2) Correlations between different observables, such as the peak luminosity and width of the light curve. Brighter is wider.

This empirical fact can be used to correct for variations in the peak luminosity to give a standard candle.

After correction, distances are accurate to $\leq 7\%$!







Different main-sequence stars make different white dwarfs.





White Dwarf



Radius: 1185 km

Mass: 0.18 Earth's

Radius: 1185 km

Mass: I.37 Sun's



A white dwarf can only have so much mass.



Single-Degenerate channel



The relative frequency of these channels is unknown.

Double-Degenerate channel

Mergers:



Collisions:



The first white dwarf smashes were calculated in 1985:

3D, 5000 particles with nuclear burning done afterwards and approximate thermodynamics.

Bottom line: Tiny amounts of ⁵⁶Ni produced.

Message: Nothing here, move along.



0.6 + 0.6 M_☉, zero impact parameter, x-y plane, temperature.

Raskin et al 2010

2010: 2 million particles with inline burning and realistic thermodynamics.

Message in 2010: Lots of interesting possibilities!



Collisions can cover the observed range of ⁵⁶Ni masses.



Exceptionally bright white dwarf supernova have been interpreted as double-degenerate events.



Observations suggest about 5 million white dwarf supernova per year within a redshift of one.



An objection to the collision scenario is the perception that such collisions are extremely rare.



Eugene Onegin and Vladimir Lensky's du<u>el</u>.

Watercolor by Ilya Repin (1899) Collisions have been believed to predominantly occur in dense stellar environments, such as cores of globular clusters.

White Dwarf Stars in Globular Cluster NGC 6397 - Hubble Space Telescope ACS/WFC



NASA, ESA, and H. Richer (University of British Columbia) = STScI-PRC07-42

Even accounting for gravitational focusing, the collision rate is ~5000 white dwarf supernovae per year within a redshift of one.

 $\sigma = \pi b^2 = \pi R^2 \left[1 + \left(\frac{v_{\text{esc}}}{v} \right)^2 \right]$

Wait! There is a 3rd body in this duel.



Eugene Onegin and Vladimir Lensky's duel.

Watercolor by Ilya Repin (1899)

Hierarchical triple star systems with white dwarf binary orbital separations of I-300 AU are known to exist.



The white dwarf binary's ellipticity can be driven to large values in a triple star system because ellipticity can be traded for inclination in the conservation of angular momentum

$$L_z = \sqrt{1 - e^2} \, \cos(i)$$

in Kozai-Lidov oscillations.









White dwarfs in a triple star system have a \sim 3% chance of experiencing a collision within 5 billion years.

If $\sim 20\%$ of white dwarfs are in triplets, the calculated supernova rate is about the same as the inferred rate.

15-20 % of $IM_{\odot} \le M \le 8M_{\odot}$ stars with a M > IM_{\odot} companion makes the collision scenario dominant.



Klein & Katz 2016

Prediction: GAIA will find ~10 new wide orbit double degenerates within 20 pc from the Sun.



This puts a strong constraint on the "triple-assisted" collision model for white dwarf supernovae.





Advances (plus a little serendipity) over the next decade should enable us to decipher the progenitors of white dwarf supernovae:

- I) Silicon, Sulfur, Calcium ratios
- 2) Unburned carbon and oxygen
- 3) Tidal tails
- 4) Sufficient number of binary WDs
- 5) Early gamma-rays
- 6) Narrow hydrogen emission or absorption
- 7) Circumstellar interaction in radio or x-rays
- 8) Gravitational wave signatures
- 9) Frequency as a function of redshift

A successful model starting from a carbon+oxygen white dwarf must make

- 0.I I.0 M⊙ ⁵⁶Ni
- 0.2 $0.4~M\odot$ Si, S, Ar, Ca
- < 0.1 Mo ⁵⁴Fe + ⁵⁸Ni
- Allow for some diversity

for the light curve for the spectrum for the nucleosynthesis for the population





0.8 + 0.6 $M_{\odot},$ zero impact parameter, density

Raskin et al 2010



t=13.999700

$0.8 + 0.6 M_{\odot}$, zero impact parameter, density, zoomed

Raskin et al 2010

